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MONTEREY, CALIFORNIA

THESIS

NAVY REQUIREMENTS FOR CONTROLLING MULTIPLE OFF-BOARD ROBOTS USING THE AUTONOMOUS UNMANNED VEHICLE WORKBENCH

by

Dennis W. Monroe

June 2007

Thesis Advisor:	Don Brutzman
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13. ABSTRACT

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This thesis examines a variety of strategic authoritative plans for autonomous vehicles to determine functional mission requirements that autonomous vehicles are expected to be performing in the near future. Excellent agreement on tactical needs and requirements was found among these diverse documents. A series of exemplar missions corresponding to specific requirements are presented as a way to explore and evaluate different tactical capabilities. These missions are then compared to the current capabilities of the AUVW by planning, running, and evaluating them in the workbench. Although the AUVW is a powerful tool it still lacks some functionality to make it tactically usable. Nevertheless, perhaps two thirds of the necessary capabilities are already supported in the workbench and further capabilities can be feasibly integrated. The result of this work is a roadmap for future work to add functionality so that the workbench can thoroughly perform user tasks in all mission areas.

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NAVY REQUIREMENTS FOR CONTROLLING MULTIPLE OFF-BOARD ROBOTS USING THE AUTONOMOUS UNMANNED WORKBENCH

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MODELING, VIRTUAL ENVIRONMENTS AND SIMULATION (MOVES)

from the

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The Autonomous Unmanned Vehicle Workbench (AUVW) is an ongoing project at NPS that allows rehearsal, real-time control, and replay of diverse autonomous unmanned vehicle (AUVs) missions. The AUVW increases the situational awareness of operators while allowing operators to learn valuable insights in a robots performance before, during, and after a mission.

This thesis examines a variety of strategic authoritative plans for autonomous vehicles to determine functional mission requirements that autonomous vehicles are expected to be performing in the near future. Excellent agreement on tactical needs and requirements was found among these diverse documents. A series of exemplar missions corresponding to specific requirements are presented as a way to explore and evaluate different tactical capabilities. These missions are then compared to the current capabilities of the AUVW by planning, running, and evaluating them in the workbench. Although the AUVW is a powerful tool it still lacks some functionality to make it tactically usable. Nevertheless, perhaps two thirds of the necessary capabilities are already supported in the workbench and further capabilities can be feasibly integrated. The result of this work is a roadmap for future work to add functionality so that the workbench can thoroughly perform user tasks in all mission areas.

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LIST OF ABBREVIATIONS AND ACRONYMS

2D	Two-Dimensional
3D	Three-Dimensional
ASDS	Advance Seal Delivery System
ASUW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
AT/FP	Anti-Terrorism/Force Protection
AUV	Autonomous Unmanned Vehicle
AUVW	Autonomous Unmanned Vehicle Workbench
AUVRG	Autonomous Unmanned Vehicle Research Group
AVCL	Autonomous Vehicle Command Language
BAMS	Broad Area Maritime Surveillance
BDA	Battle Damage Assessment
C2	Command and Control
CN3	Communication, Navigation Network Nodes
CNO	Chief of Naval Operations
DDS	Dry Deck Shelter
DEAD	Destruction of Enemy Air Defense
DIS	Distributed Interactive Simulation
DoD	Department of Defense
DoN	Department of the Navy
EA	Electronic Attack
EOD	Explosives Ordnance Disposal
ESG	Expeditionary Strike Group
EXW	Expeditionary Warfare
EW	Electronic Warfare
FOUO	For Official Use Only
GIS	Geospatial Information Systems
GPS	Global Positioning System
GUI	Graphical User Interface
GWOT	Global War on Terror

HSI	Human-Systems Integration
HTML	Hypertext Markup Language
I18N	Internationalization
ID	Identification
IED	Improvised Explosive Device
IEEE	Institute of Electrical and Electronic Engineers
ISO	International Standards Organization
ISR	Intelligence, Surveillance, and Reconnaissance
JAUS	Joint Architecture for Unmanned Systems
JRP	Joint Robotics Program
JSF	Joint Strike Fighter
LCS	Littoral Combat Ship
MCM	Mine Countermeasures
MIED	Maritime Improvised Explosive Device
MIO	Maritime Interdiction Operation
MIW	Mine Warfare
MMA	Multi-Mission Aircraft
MOVES	Modeling, Virtual Environments and Simulation
NAS	National Academy of Sciences
NPS	Naval Postgraduate School
OODA	Observe-Orient-Decide-Act
OS	Operating System
OSD	Office of the Secretary of Defense
PDU	Protocol Data Unit
RC	Remote Control
RDF	Resource Description Framework
RHIB	Rigid Hull Inflatable Boat
RMS	Remote Mine-Hunting System
RSTA	Reconnaissance, Surveillance, and Target Acquisition
SAVAGE	Scenario Authoring and Visualization for Advanced Graphical Environments
SEAD	Suppression of Enemy Air Defense

SMAL	Savage Modeling and Analysis Language
SOF	Special Operations Forces
SSBN	Ballistic Missile Submarine
SSGN	Guided Missile Submarine
SSN	Attack Submarine
STOM	Ship to Objective Maneuver
SUW	Surface Warfare
TCS	Time Critical Strike
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
UXO	Unexploded Explosive Ordnance
X3D	Extensible 3D
XHTML	Extensible Hypertext Markup Language
XML	Extensible Markup Language
XSL	Extensible Stylesheet Language
XSLT	Extensible Stylesheet Language Transformation

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I. INTRODUCTION

A. PROBLEM STATEMENT

The Autonomous Unmanned Vehicle Workbench (AUVW) is an ongoing project at the Naval Postgraduate School (NPS) that allows planning, rehearsal, real-time control, and replay of diverse autonomous unmanned vehicle (AUV) missions. Since AUVs have gained an increasingly important role on the battlefield, a tool for interoperable AUV control is needed. The AUVW increases the situational awareness of operators by allowing them to learn valuable insights into a robot's performance before, during, and after a mission.

This thesis examines a variety of strategic plans for autonomous vehicles to determine the functional mission requirements of autonomous vehicles in the near future. The future missions of autonomous vehicles are then compared to the current capabilities of the AUVW, which provides a roadmap for capabilities that need to be added to the AUVW to support future robot operations.

B. MOTIVATION

Autonomous vehicles are gaining a more prominent military role during both peacetime and conflict. Autonomous vehicles perform numerous missions on land, in the air, and at sea. There are four categories of autonomous unmanned vehicles: Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs), Unmanned Surface Vehicles (USVs), and Unmanned Underwater Vehicles (UUVs). Each vehicle type has advantages and disadvantages relative to other vehicle types. Different vehicle types are expected to perform different missions and sometimes even perform missions together. This thesis only covers UAVs, USVs, and UUVs because those are the vehicles most commonly used by the Navy.

The AUVW can bridge the interoperability gap that becomes an issue either when different robots operate together or when an operator has to control different robots. Each robot typically has a different command language and control interface. If unmanned vehicles are going to effectively assume an increased role in future

battlefields, users will have to learn multiple control systems unless a common protocol is developed. Such an approach is impractical and hazardous. The AUVW has a solution to interoperability through the Autonomous Vehicle Command Language (AVCL), which can be mapped to any robot. AVCL can send commands to multiple types of robots and can allow users to learn only one control interface. Rehearsal and replay using realistic physics-based controllers and dynamics response provides high-fidelity analysis capabilities.

Throughout the world, other countries are trying to utilize unmanned vehicles. Unmanned vehicles have shown their usefulness in combat in the last few years while remaining relatively inexpensive. The Armed Forces of the United States of America needs to leverage the technology of autonomous vehicles in order to maximize their effectiveness. The Naval Postgraduate School has many research efforts working to extend the capabilities to maximize the effectiveness of AUVs. The AUVW is one of those efforts to maximize the affects of AUVs.

C. OBJECTIVES

This thesis work addresses the following questions:

- What are AUV roles in the future US Navy?
- What are the operator interface requirements for supporting multiple UUVs, USVs, and UAVs?
- What are the current capabilities of the AUVW?
- How well does the AUVW meet the projected needs of the Navy?
- What capabilities does AUVW need to improve or develop in order to meet the needs of the Navy?

D. THESIS ORGANIZATION

The first chapter identifies the purpose and motivation behind conducting this research and establishes the goals for the thesis. The second chapter covers related work relevant to the AUVW. The third chapter covers why autonomous vehicles are important to the United States Navy. The fourth chapter examines various authoritative documents

that outline the missions expected from AUVs. The fifth chapter introduces the AUVW and its capabilities. The sixth chapter shows exemplar missions that the AUVW can support corresponding to each of the overarching mission requirement areas. The final chapter covers thesis conclusions and presents recommendations for future work.

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II. RELATED WORK

A. INTRODUCTION

The NPS Autonomous Underwater Vehicle Research Group (AUVRG) has existed since 1987. Prototype versions of the AUVW were created in 1992 and 1994 with ongoing improvements and revisions ever since (Brutzman "A Virtual World," Brutzman "NPS AUV Integrated Simulation"). Every year the capabilities of the AUVW are expanded through the efforts of students and faculty in a wide variety of departments including: Modeling, Virtual Environments and Simulation (MOVES), Mechanical Engineering, Computer Science, and multiple engineering fields. This chapter covers the motivation behind the workbench, the technologies utilized by the workbench, how the workbench has been used for simulation, and work done to reduce interoperability issues with robots.

B. MOTIVATION FOR CREATING THE AUTONOMOUS VEHICLE WORKBENCH

Autonomous vehicles are expected to complete a wide variety of missions in various environmental conditions. "It is tremendously difficult to observe, communicate with and test underwater robots, because they operate in a remote and hazardous environment where physical dynamics and sensing modalities are counterintuitive" (Brutzman iii). To test to see if a robot was programmed correctly the robot had to be placed in a test tank (Burns 12). This is why a virtual world is important for AUVs. Simulating the robots in their environment became a critical development issue because autonomous vehicles are not easily replaceable, especially for research universities and ships at sea. Testing the engineering and programming changes in a tank is a time-consuming evolution with many variables. A virtual world eliminates the need for a test tank to debug code through simulation. "Visualization of robot interactions in an underwater virtual world improves our perceptual ability to evaluate robot performance" (Brutzman "A Virtual World" 226). Figure 1 shows an early physics-based robot demonstration. Upon adding support for multiple vehicle types including UAVs and

USVs, the Autonomous Underwater Vehicle Workbench became known as Autonomous Unmanned Vehicle Workbench. Table 1 lists the thesis work related to the AUVW.

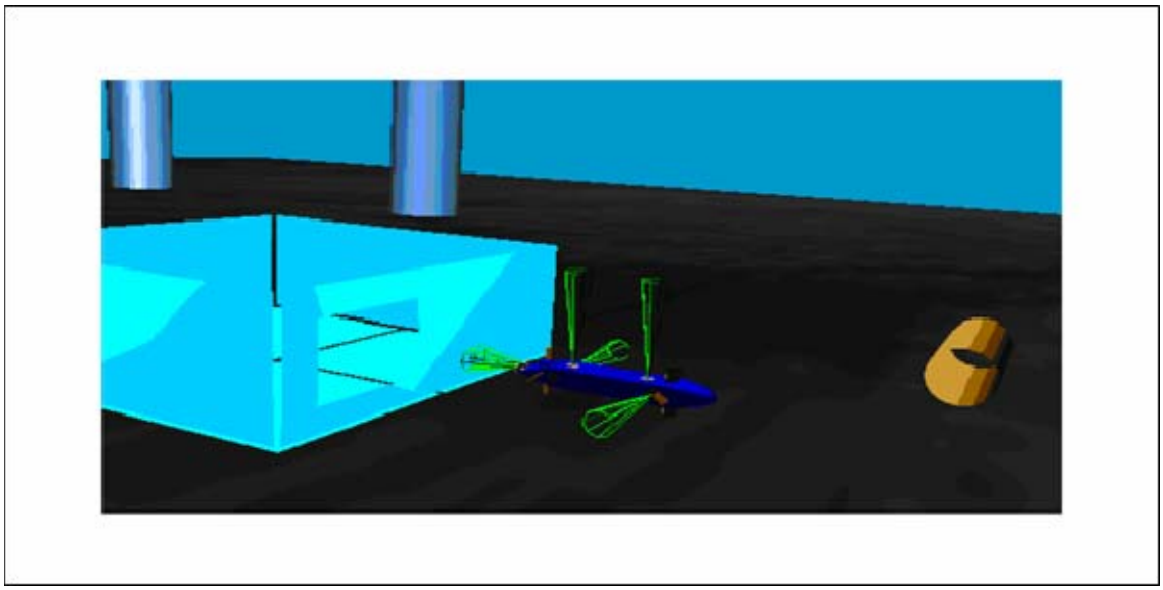

Figure 1. An early visual representation used to see AUVs in a virtual world from (Brutzman "A Virtual World," 221)

Author	Title
Ayala	*Execution Level Java Software and Hardware for the NPS Autonomous Underwater Vehicle*
Boncal	*A Study of Model Based Maneuvering Controls for Unmanned Vehicles*
Burkley	*An Acoustic Sensor History Server for a Submarine Combat Control System*
Burns	*Merging Virtual and Real Execution Level Software for the Phoenix Autonomous Underwater Vehicle*
Byrne	*Real Time Modeling Cross Body Flow Torpedo Tube Recovery*
Davis	*Precision Control Maneuvering Docking In Tube*
Fodrea	*Obstacle Avoidance Control Remus Autonomous Underwater Vehicle*
Hawkins and Van Leuvan	*AN XML-Based Mission Command Language for Autonomous Underwater Vehicle*
Holliday	*Real-Time 3D Sonar Modeling and Visualization*
Johnson	*AUV Steering Parameter Identification for Improved Control Design*
Kucik	*"Follow the Leader" Tracking by Autonomous Underwater Vehicles (AUVs) Using Acoustic Communications and Ranging*
Leaver	*VRML Terrain Modeling for the Monterey Bay National Marine Sanctuary (MBNMS)*
Lee	*AUV Workbench: Collaborative Environment for Autonomous Underwater Vehicles (AUV) Mission Planning and 3D Visualization*
Leonhardt	*Mission Planning and Mission Control for the Phoenix Autonomous Underwater Vehicle Implementation and Experimental Study*
Neushul	*Interoperability, Data Control and Battlespace Visualization using XML, XSLT AND X3D*
Norbraten	*Utilization of Forward Error Correction Techniques with Extensible Markup Language Schema-Based Binary Compression Technology*
Rauch	*Savage Modeling Analysis Language (SMAL): MetaData for Tactical Simulations and X3D Visualizations*
Rosetti	*Tactical Web Services: Using XML and Java Web Services to Conduct Real-Time Net-Centric Sonar Visualization*
Seguin	*Simulating Candidate Missions for a Novel Glider Unmanned Underwater Vehicle*
Serin	*Design and Test of the Cross Format Schema Protocol for Networked Virtual Environments*
Stone	*A Rapidly Reconfigurable Application Layer, Virtual Environment Network Protocol*
Zeswitz	*Integration of Distributed Interactive Simulation Protocol for Communication Architecture and Information Interchange*

Table 1. The different theses related to the AUVW done through the years and can be accessed at http://xmsf.cvs.sourceforge.net/xmsf/AuvWorkbench/documentation/theses

C. TECHNOLOGIES EMPLOYED BY THE AUVW

Figure 2 shows the dataflow of the AUVW and how different technologies fit together to make the AUVW work. This section explains why open source technologies were chosen for the AUVW and the technologies employed by the workbench. Current work focuses on the utilization of improved bathymetry models and the production of robot-telemetry mission data archives in support of AUV Fest 2007, June 1-14 off Panama City Florida.

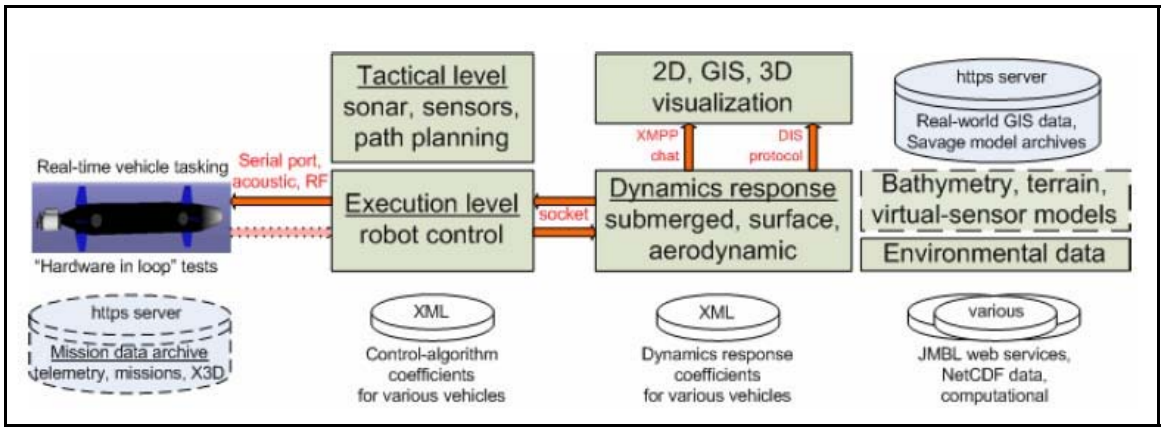

Figure 2. AUVW uses multiple technologies for its functionality including DIS, Java, X3D, and XML

1. Why Open Source?

The AUVW uses only open source technologies and does not use proprietary software. The reason is cost and sustainable development. Open source technologies are free. The government does not have to pay license fees for the program that the AUVW uses. However, typically some sponsor has to pay for programmer support to add new functionality to the open source program. That addition is open to subsequent use by operators and researchers, and government does not have to keep paying for the same thing repeatedly as with proprietary software. Perhaps most importantly, improvements and corrections can be openly applied without legal restrictions.

2. Internationalization (I18N)

The United States is not the only country using AUVs. When robots from the US work with robots from other countries, the language barrier can be an issue when planning missions. The AUVW can reduce the language barrier through translating functional menus and tool tips to any language. This allows multiple users from different countries to plan and share AVCL missions with the same tool, which allows for an easy transfer of information. This is important if robots from different countries are operating in close proximity to each other, or cooperatively working together to achieve a mission. Table 2 shows how many countries already use UAVs. Similar growth is likely for USV and UUV operations.

MTCR Member*	UA Exporter	UA Operator	UA Manufacturer	UA Developer
Argentina	no	yes	yes	yes
Australia	yes	yes	yes	yes
Austria	yes	no	yes	yes
Belgium	no	yes	yes	yes
Brazil	no	no	no	no
Canada	yes	no	yes	yes
Czech Republic	no	yes	yes	yes
Denmark	no	yes	no	no
Finland	no	yes	no	no
France	yes	yes	yes	yes
Germany	yes	yes	yes	yes
Greece	no	no	no	yes
Hungary	no	no	no	yes
Iceland	no	no	no	no
Ireland	no	no	no	no
Italy	yes	yes	yes	yes
Japan	yes	yes	yes	yes
Luxembourg	no	no	no	no
The Netherlands	no	yes	no	no
New Zealand	no	no	no	no
Norway	no	no	no	yes
Poland	no	no	no	no
Portugal	no	no	no	yes
Russia	yes	yes	yes	yes
South Africa	yes	yes	yes	yes
South Korea	no	yes	yes	yes
Spain	no	no	yes	yes
Sweden	no	yes	yes	yes
Switzerland	yes	yes	yes	yes
Turkey	yes	yes	yes	yes
Ukraine	yes	yes	yes	yes
United Kingdom	yes	yes	yes	yes
United States	yes	yes	yes	yes
*Although not a member of the MTCR, Israel has pledged to abide by its guidelines.				

Table 2. Many different countries use UAVs. (Office of the Secretary of Defense 40)

3. Java Look + Feel

The AUV Workbench user interface is built using the Java Look and Feel guidelines. These guidelines allow the AUVW to support users who use different languages. Platform independence is a key capability of Java. To date, the AUV Workbench has been used with Windows, Mac OS X, and Linux. Java Look and Feel is designed to provide consistency in the appearance and behavior of common design elements, compatibility with industry-standard components and interaction styles, and aesthetic appeal that does not distract from application content ("Java Look and Feel Design Guidelines"). Any button in the AUVW can also be found in the menu bars with the same tool tips. Tool tips are created to offer hints to the user on the functionality of each feature. Java Look and Feel provides the backbone in which the AUVW was built upon. Further work is planned for demonstrating improved Human-Systems Integration (HSI) using the AUV Workbench.

4. Extensible Markup Language (XML)

XML is the language used for all data associated with the AUV Workbench, in particular AVCL. The user does not have to know XML to be able to use the AUVW. Through the graphical user interface (GUI), the user can edit the XML without realizing they are using XML. XML is composed of tags. The following section explains why XML was chosen for AUVW. Figure 3 shows an XML file from a UAV mission in the AUVW.

```
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<AVCL version="1.0" xsi:noNamespaceSchemaLocation="AVCL.xsd" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance">
  <head>
    <meta content="AVCL 1.0 mission generated via XSLT from ACL 0.1 (AUV missions only) mission." name="description"/>
    <meta content="Fall 2004" name="created"/>
    <meta content="9 August 2005" name="revised"/>
  </head>
  <body>
    <MissionPreparation>
      <UnitsOfMeasure angle="degrees" distance="meters" mass="kilograms" time="seconds"/>
      <GeoOrigin latitude="47.685001373291016" longitude="-122.61000061035156"/>
      <Configuration>
        <UnmannedAerialVehicle/>
      </Configuration>
      <UAVCommandScript description="Scripted UAV mission.">
        <MakeKnots speedOverGround="false" value="50.0"/>
        <SetPosition>
          <XYPosition x="0.0" y="-0.0"/>
          <MSLAltitude value="500.0"/>
        </SetPosition>
        <Waypoint>
          <XYPosition x="3000.0" y="0.0"/>
          <MSLAltitude value="500.0"/>
          <Knots value="70.0"/>
        </Waypoint>
        <Waypoint>
          <XYPosition x="3000.0" y="1500.0"/>
        </Waypoint>
        <Waypoint>
          <XYPosition x="-0.0" y="1500.0"/>
        </Waypoint>
        <Quit/>
      </UAVCommandScript>
    </MissionPreparation>
  </body>
</AVCL>
```

Figure 3. An XML file of a scripted mission for an UAV.

a. XML in 10 Points

The best way to describe XML is through the ten points that Bert Bos composed (Bos). These ten points summarize what XML is in a quick and conscience manner. The ten points are: XML is for structuring data, XML looks like HTML, XML is text, but is not meant to be read, XML is verbose by design, XML is a family of technologies, XML is new, but not that new, XML leads HTML to XHTML, XML is modular, XML is the basis for RDF and the Semantic Web, and XML is license-free, platform-independent and well-supported. This section explains the relevant points on why XML was chosen for the AUVW. Further details available in (Davis).

1. XML is for structuring data. XML has rules to structure data, but at the same time, it is not a programming language like Java. The structure allows computers to easily generate and read data. This is how the AUVW is able to create missions for robots and read missions.

2. XML looks like HTML. XML looks familiar because it uses a similar structure as HTML. XML uses tags that form a tree structure and attributes which can give values to the data. However, there are not preset tags in XML like there are in HTML. This allows the user to define the tags and attributes to best describe the data. Tags give meaning to the data.

3. XML is text, but is not meant to be read. XML is meant to be read by machines. At the same time, it is easily, readable which means the user could debug the XML file or understand the data presented in the file. This feature of XML allows users to analyze the data to know if a mission in the AUVW performs how it was programmed to.

4. XML is verbose by design. XML needs to be verbose because it is human readable for the reasons explained in the previous point. However, this is one of XML's weaknesses because it is hard to transmit large files in operating areas due to network and battery power limitations. However, XML can be compressed to reduce its size. The telemetry mission file for robots can be over one megabyte large, however, compression can make that same file around seventy percent smaller.

5. XML is a family of technologies. "Extensible Style Sheets (XSL), Extensible Stylesheet Language Transformation (XSLT), and Document Object Model (DOM) are included in this family of technology. They all play in concert to make XML a powerful tool" (Weekley et al. 2). XSLT in particular allows any XML file to be transformed into any format necessary.

6. XML is new, but not that new. XML has been around since 1996, which means that people know how to use it. This allows the workbench mission to be understood by users who know XML. XML format is also familiar to people who have experience with HTML. This allows the workbench to have a quick learning curve for users wanting to know how the workbench works. The AUVW, however, does not require the user to know any XML. A user using the AUVW can program a mission in XML without even knowing it because the workbench can prepare and run missions through an interface that hides the XML.

7. XML leads HTML to XHTML. "XHTML is the XML-compliant version of HTML" (Weekley et al. 2).

8. XML is modular. "Through the namespace mechanism, XML allows you to define a new document format by combining and reusing other formats" (Weekley et al. 2).

9. XML is the basis for RDF and the Semantic Web. "W3C's Resource Description Framework (RDF) is an XML text format that supports resource description and metadata applications. When the data is self-describing, other technologies can 'crawl' through the data and discover, combine and reformat data in interesting ways" (Weekley et al. 2).

10. XML is license-free, platform-independent, and well supported. XML is free for anyone to use and can be created using a simple text editor. This feature of XML allows it to continue growing each year. In addition, by being free XML allows for unencumbered development of the workbench. XML is also platform-independent which means it can work on Windows, Mac, or another operating system.

b. Verification

XML can be verified that the XML file is both legal and well formed. This means that all the rules of the language are followed like if a tag is opened it has to be closed or a child element is nested within the parent element. This is important to the AUVW because it tells the user if there is a problem with the code even before running the mission. XML editors can tell the user where and what the error is. This allows the user to easily fix any problems in the mission.

c. Validation

A schema is an XML document that allows a programmer to define what information needs to be in an XML document and what format it needs to be in. XML through a schema can check and make sure that values entered into the tags are in a valid range. The schema used for the AUVW is AVCL. The AVCL schema ensures that only valid commands are given. For instance, numeric values within a certain range for each command are allowed and letters are not permitted. Validation can tell users why the

data is incorrect and will ensure that only valid missions are created. Also, through a schema one can make sure that certain fields that are required actually contain data like what type of vehicle the mission is for. This makes sure that a mission for a UAV is going to allow different parameters than for a UUV. Validation of an XML file allows users to know before the mission is tested if any commands are illegal.

d. XSLT

The true power of the XML is in the ease of conversion using XSLT. XSLT is a way to change an XML document into another XML file, text file, or some other format. An XSLT Stylesheet allows missions made in the workbench to be converted into Extensible 3D Graphics (X3D) to allow the visualization of that mission. Also, XSLT can convert the missions made in the workbench into any unique command language that a robot might have. This allows the workbench to be a tool that can adapt to any vehicle that is currently in use, or a vehicle that might be made in the future.

5. Extensible 3D Graphics (X3D)

X3D is an open standard by the International Standard Organization (ISO) for generating 3D graphics on the web. X3D is also free for anyone to use and there are no fees associated with it. X3D is used when creating the robots for the AUVW. Since it is free and relatively simple to learn anyone can create future robots and plug them into the AUVW.

6. Xj3D

Xj3D is the open-source rendering implementation for the X3D graphics standard, which is free to use. It is “a Java-based toolkit developed by Yumetech that allows companies to rapidly support X3D” ("The Cover Pages: X3D Final Working Draft"). Xj3D is the browser that is used in the AUVW to allow users to view and navigate through a 3D scene.

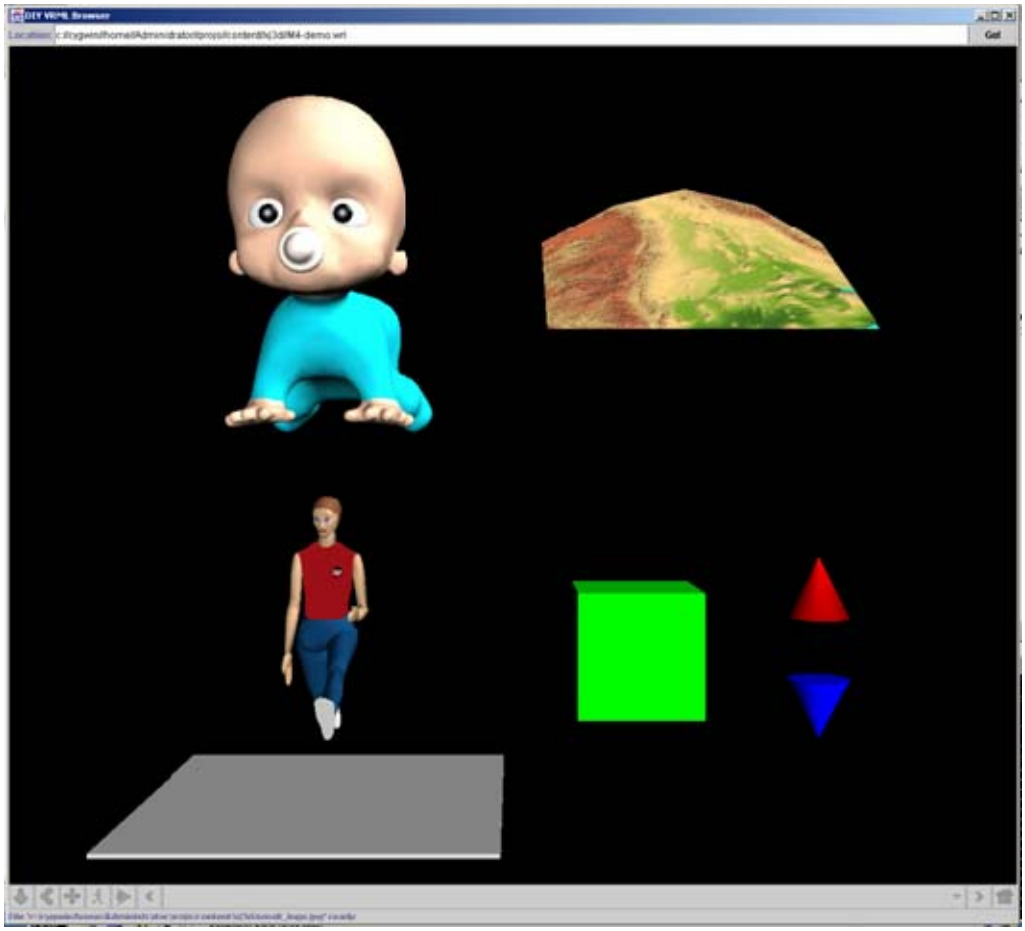

Figure 4. Xj3D browser can support shapes, terrain, and even humanoids from ("The Xj3D Project - Screenshots")

7. Distributed Interactive Simulation (DIS)

"Distributed Interactive Simulation (DIS) is a government/industry initiative to define an infrastructure for linking simulations of various types at multiple locations to create realistic, complex, virtual worlds for the simulation of highly interactive activities" (IEEE 4). DIS sends out protocol data units (PDUs) which contain information about the following areas: Entity Information/interaction, Warfare, Logistics, Radio Communications, Distributed Emission Regeneration, Simulation Management, Synthetic Environment, Entity Management, Minefield, Live Entity Information/Interaction, and Non-Real Time Information (IEEE, 13). DIS allows the workbench to simulate any mission area presented in the various master plans.

DIS works by giving a vehicle a unique identification. PDUs also contain information about that vehicle like its X, Y, Z position, and roll, pitch, and yaw angles. These packets are received by a simulation. The simulation then uses the vehicle ID to determine which vehicle it belongs to. It then updates the vehicle's position and status in the X3D world. DIS can be used through the loop-back adapter on a computer so a user can use the workbench while not connected to the internet. In addition, tunnels through the internet can route DIS packets. This allows multiple people who are located around the world to be able to visualize the same mission distributable.

8. Physics in the Loop

The key in rehearsing a mission is knowing how the robot will react to the commands given in the environment it is operating. An improper order can lead to an unachievable command and systems failures like a UAV diving too steeply. The AUVW has the parameters for the environment and for each vehicle. This allows six degree of freedom physics for a rehearsal of a robot mission, which allows operators to see an accurate representation of the mission before the mission is actually preformed. Aerodynamic and hydrodynamic models provide this high-fidelity response.

9. X3D Earth

X3D Earth is another ongoing project at NPS to make an open source 3D model of the Earth's terrain and bathymetry. When X3D Earth becomes available it will be a powerful tool for the AUVW to utilize, because an operator of a robot anywhere in the world will be able to visualize the terrain that the robot is expected to maneuver through. Currently, only cities and ports have been made with X3D Earth and ongoing work is providing a complete X3D world, both for terrain and bathymetry. Further information is available at the X3D Earth working group page, http://www.web3d.org/x3d-earth.

D. USING AUVW FOR SIMULATION

The Scenario Authoring and Visualization for Advance Graphical Environments (SAVAGE) Research Group is currently working on both the AUVW and Savage Studio. Savage Studio's inspiration came from the USS COLE attack. The motivating goal for Savage Studio is to provide an analytic tool in helping commanders find weaknesses in

their defensive strategy against terrorist attacks. The technologies utilized by the Savage Studio are the same used by the AUVW: standards-based, open source, and platform independent.

Savage Studio creates both X3D scenes and discrete event simulations. This is different from a time-step simulation such as the workbench, which advances the simulation clock at a fixed rate. A discrete event simulation can advance the simulation clock at short or long intervals depending on model requirements. Scenarios for Savage Studio are generated with Viskit. Viskit is a visual programming development environment for agent-based Simkit models, which can automatically create Java for the logic of the response when an event occurs. As an example of an agent model, if a patrol craft detects a boat in a restricted area, the patrol craft will investigate the boat.

Viskit can incorporate randomness in simulation through a random number generator to approximate realistic degree of uncertainty; providing probability-based inputs and responses. Viskit logic can be run thousands of times and a statistical distribution characterizing a model's overall response can thus be developed.

A further capability of a high-fidelity physics-based simulation is to determine how effective a vehicle might be during the design phase. The advantage of simulation is that it is much cheaper to evaluate than actually making a vehicle and then testing it. The AUVW provides the ability to test future vehicles and their effectiveness. John Seguin's thesis tests the effectiveness of a glider that is in the development phase by using Viskit. In turn, the AUV Workbench was used to visually verify that the missions created by Viskit made sense. Figure 5 shows a sample mission Viskit created for the workbench.

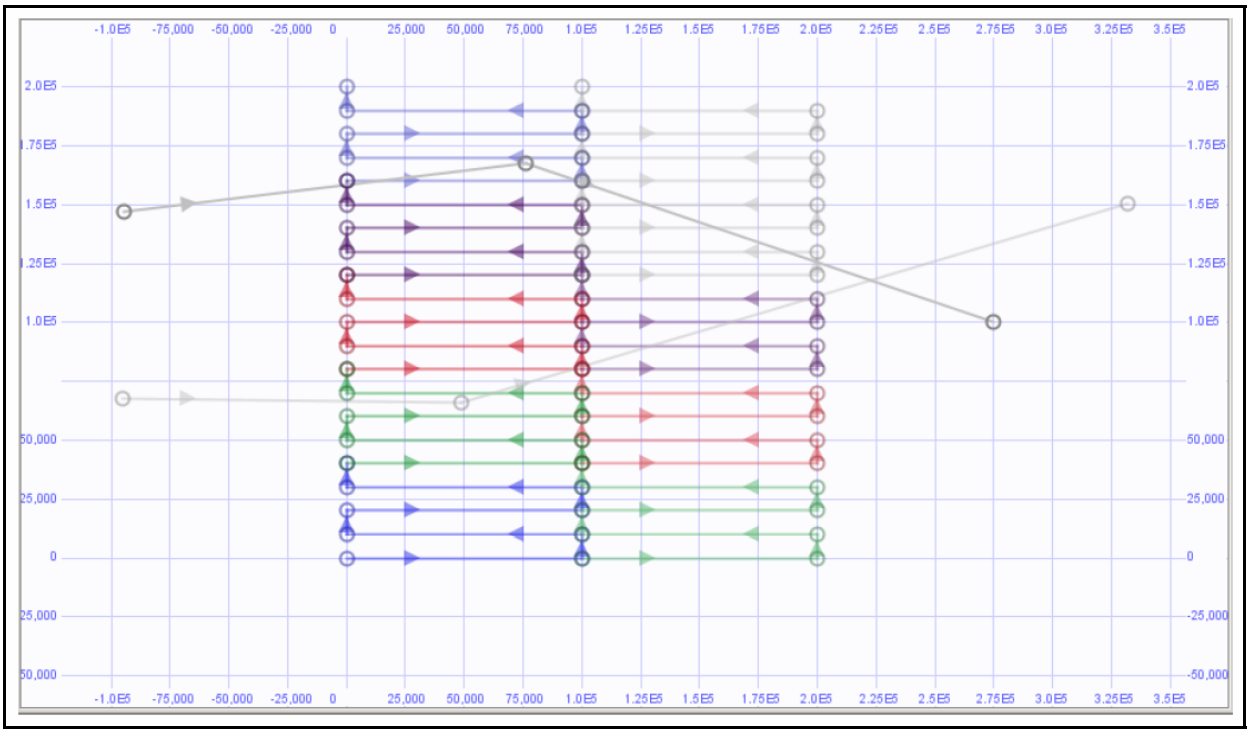

Figure 5. Visual validation that a mission created with Viskit makes sense. This plot shows ten Seadriver glider UUVs searching for two transiting targets. From (Seguin 88)

E. INTEROPERABILITY

One of the greatest problems with unmanned vehicles is a lack of interoperability. There are over seventy different types of UUVs in operation currently in the Navy (O'Rourke, "Unmanned Vehicles" 4). These robots typically do not have a common command language and an operator typically has to know how to uniquely program missions in each robot. Although the Joint Architecture for Unmanned Systems (JAUS) improves this situation slightly, it is oriented towards internal robot components and not robot tasking (Department of Defense (DoD) Joint Robotics Program (JRP) 4-10). To solve this problem, the Autonomous Vehicle Command Language (AVCL) was created. AVCL is covered in detail in Chapter V.

F. SUMMARY

This chapter briefly covered the major research areas of the AUVW: the motivation for creating the AUVW, technologies utilized by the workbench, using the AUVW for simulation, and interoperability issues. The AUVW was created to test how a

robot will perform a mission without actually operating the robot. The AUVW is developed with open-source programs, which makes it free to use. The AUVW with the aid of Viskit has the capability of testing a robot while the robot is still in the design phase. Through the use of AVCL, the AUVW has the capability to eliminate the interoperability issue facing robots.

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III. AUV RATIONALE

A. INTRODUCTION

Robots have a major role on the battlefield and have become a valuable military asset. This chapter explains how future combat platforms are incorporating AUVs, what is meant by the term AUV, and their importance to today's naval operations.

B. FUTURE COMBAT PLATFORMS

The Navy is in a transition period and acquiring new warfare platforms. The Navy is adding Virginia class submarines to the fleet to replace the Los Angeles class submarines. Also, four of the Ohio class submarines are completing conversions from ballistic missile submarines (SSBN) to conventional guided missile submarines (SSGN). The surface fleet expects to add the Littoral Combat Ship (LCS) in the next few years. This is the first step to modernize the surface fleet, which also plans to add the DDG(X) and CG(X) to the fleet. Naval aircraft are also being modernized with the F-18 Super Hornet replacing the F-14 Tomcat, the possible addition of the Joint Strike Fighter (JSF) in the next few years, and the P-8 Multi-Mission Aircraft (MMA) replacing the P-3 Orion.

Numerous opportunities present themselves for the use of unmanned vehicles in future combat platforms. This section examines how the Virginia class submarine, SSGN, Littoral Combat Ship, and the P-8 Poseidon aircraft might utilize unmanned vehicles to help them accomplish their missions.

1. Virginia Class Submarine

The first Los Angeles class submarine was commissioned in 1976. The main mission of submarines during the Cold War was to hunt other submarines. At the turn of the millennium, the Seawolf class submarine was designed to be the best sub hunter in the world and a possible replacement for the Los Angeles Class submarine. However, after the Cold War the primary role of the attack submarine shifted from sub hunter to a multi-mission platform with an additional emphasis on covert operations. Attack submarine's mission roles include covert intelligence surveillance reconnaissance (ISR)

missions, covert special operation forces (SOF) operations, covert strike missions with Tomahawk missiles, mine warfare (MIW), anti-submarine warfare (ASW), and anti-surface warfare (ASUW) (O'Rourke, “Navy Attack Submarine” 7).

The Seawolf class submarines are some of the most advanced submarines in the world; however, the Seawolf class had a steep price tag of three billion dollars each ("Seawolf Class Attack Submarine"). The Navy initially planned to build thirty Seawolf class submarines (O'Rourke, “Navy Attack Submarine” 11). However, only three Seawolf submarines were constructed: SEAWOLF, CONNECTICUT, and JIMMY CARTER as the priorities of the Navy shifted to the newer Virginia Class submarine.

The Virginia class is a multi-mission submarine that utilizes a great deal of its technology from the Seawolf class. The Virginia class is a more cost-effective replacement for the Los Angeles class submarine costing 2.3 billion dollars with plans of reducing the price tag to two billion dollars (O'Rourke, “Navy Attack Submarine” 2). Mission areas for the Virginia class submarine include the traditional sub hunter role, expanded to also perform missions in the littorals. The Virginia class submarines have a special lock-out/lock-in chamber to support SOF missions (Connor). Unmanned underwater vehicles are expected to become an important asset in aiding the Virginia Class submarine to perform its missions. The Navy plans to build two Virginia class submarines per year.

2. Guided Missiles Submarines SSGN

The Navy decided that fourteen ballistic missile submarines (SSBN) are needed to accomplish the national mission of strategic deterrence. However, the Navy had eighteen SSBNs. Instead of mothballing the four oldest ballistic missile submarines, since each had, over twenty years of useful service left, the Navy converted the USS OHIO, USS GEORGIA, USS PENNSYLVANIA, and the USS MICHIGAN into SSGNs (O'Rourke, “Navy Attack Submarine” 7). The conversion of the four submarines cost 4.018 billion dollars total, making these upgrades a relative bargain (O'Rourke, “Navy Trident Submarine Conversion” 1).

The SSGNs retain the twenty-four large-diameter missile tubes originally used to house the Trident D-5 missiles, but the tubes are converted to perform other missions. Tubes one and two are lockout chambers that can connect either a dry deck shelter (DDS) or an advance SEAL delivery system (ASDS) (O'Rourke, "Navy Trident Submarine Conversion" 3). SSGNs have the berthing capacity and storage support for over sixty SOF personnel. The other twenty-two tubes have been configured to hold seven Tomahawks for a total of 154 missiles. Depending if the SSGN has to support SOF operations with a need for more supplies than what the DDS can hold, tubes three to ten can hold supplies instead of missiles (O'Rourke, "Navy Trident Submarine Conversion" 3). This variation reduces cruise missile capacity from 154 to 98, but still allows the SSGN sufficient flexibility to complete any assigned mission.

The SSGN can be a significant asset for a combatant commander, providing the firepower and the ability to support forward-deployed SOF operations. SSGNs will operate with a blue and gold crew rotation similar to SSBNs, in order to maximize time spent deployed overseas. This approach allows at least one SSGN to be forward deployed at any given time (O'Rourke, "Navy Trident Submarine Conversion" 3). SSGNs are also designed to support large-diameter UUVs. Large-diameter UUVs fit into the missile tubes and have longer endurance than smaller UUVs because they can carry more batteries. Large-diameter UUVs have diameters between 36 to 72 inches with weights of up to 20,000 pounds (O'Rourke, Unmanned Vehicles 5). The mission areas of large-diameter UUVs are "persistent ISR, ASW, long-range oceanography, mine warfare, special operations, EOD, and time-critical strike operations (O'Rourke, "Unmanned Vehicles" 5).

3. Littoral Combat Ship (LCS)

The LCS is being developed to help the Navy meet new mission areas because the Navy does not have a ship that can adequately perform in the littoral areas. The LCS will have the capability to go 45+ knots, and has a shallow draft to support in-shore operations (O'Rourke, "Navy Littoral Combat Ship" 5). "The LCS is a small, fast surface combatant that uses modular 'plug-and-fight' mission payload packages, including

unmanned vehicles" (O'Rourke, "Navy Littoral Combat Ship" 4). Different equipment modules will be able to be plugged-in to the LCS to help perform a choice of different mission areas, all while using one common platform. Modularity also allows the LCS to accommodate new mission modules in order to accomplish future missions not yet anticipated.

Unmanned vehicles are vital to the success of the LCS in the littorals. Unmanned vehicles can alert the crew of possible threats at far greater ranges than are possible using onboard sensors alone. Unmanned vehicles will be a force multiplier for the LCS allowing it to be more affective. The mission areas for the LCS are mine warfare, anti-submarine warfare, operations against small boat attacks, ISR, maritime intercept operations (MIO), SOF support; and logistics support for movement of personnel and supplies (O'Rourke, "Navy Littoral Combat Ship" 5). The Navy is developing a helicopter UAV called the Fire Scout to help the LCS perform surveillance missions (O'Rourke, "Unmanned Vehicles" 2). The LCS will also have the Remote Mine-Hunting System (RMS) which is a USV to help perform mine-warfare missions (O'Rourke, "Unmanned Vehicles" 4).

The LCS is expected to cost over 220 million dollars and help the Navy perform as a brown water navy (O'Rourke, "Navy Littoral Combat Ship" 5). The Navy plans on acquiring over fifty LCS platforms by 2016 (O'Rourke, "Navy Littoral Combat Ship" 4). The modularity of the LCS will make it an effective combat platform even if it has to perform missions not yet anticipated. These modules will include UAVs, USVs, and UUVs, which presents unique challenges of maintenance, launch, and recovery to future crews of Littoral Combat Ships.

4. Poseidon P-8

The P-3 Orion has been in service since the 1960s, and it is time for it to be replaced by the P-8 Poseidon. The P-8 design is a converted Boeing 737 airframe that is projected to be introduced into service by 2013. The projected mission areas for the P-8 include ASW, ASuW, monitoring sea traffic, conducting strike missions, and performing

ISR missions (“Sea Shield”). The P-8 will use unmanned vehicles because of the wide areas that need to be searched. The Broad Area Maritime Surveillance (BAMS) are UAVs that will assist the P-8 in accomplishing its missions. The BAMS can provide persistent ISR over large areas and can orbit the earth up to five orbits (“Integrated Systems Unmanned Systems: Global Hawk”). “The BAMS UAS missions will include, but are not limited to, maritime surveillance, collection of enemy order of battle information, battle damage assessment, port surveillance, communication relay, and support of the following missions - maritime interdiction, surface warfare, battlespace management, and targeting for maritime and littoral strike missions” ("Integrated Systems Unmanned Systems: Global Hawk"). Due to the speed and altitude that the Poseidon will operate at it most likely will not launch any unmanned vehicles. Rather it probably will rely on unmanned platforms that are already deployed. Nevertheless, naval launch mechanisms are possible and cooperative engagement with other naval ships, submarines, and unmanned vehicles is guaranteed.

C. WHAT IS AN AUV?

1. What is a Robot?

There are different definitions and ideas on what exactly is meant by the term robot. One good definition is, “An intelligent robot is a mechanical creature which can function autonomously” (Murphy, 3). A robot is more than a machine that is pre-programmed to do a task repeatedly. Rather, a robot reacts to its environment. An intelligent robot typically follows a three-step cycle: sense, plan, and act. This is similar to the observe, orient, decide, and act (OODA) loop used in military operations. Through its sensors, a robot is aware of what is occurring in its environment. The sensors collect information that the robot then uses to update an action plan. Once the plan is ready, the robot continues to execute the plan and the robot repeats the cycle indefinitely. Some robots are also able to learn from experiences.

There has been a long-standing debate on whether or not a robot is actually intelligent. Artificial intelligence does not have a single accepted definition. Chess computers have been able to beat grandmasters, but does that necessarily mean the program is intelligent? Perhaps a chess program “just” looks at all the possible moves for

twenty or thirty moves ahead and then picks the best move. Such an activity can be explained and programmed by humans, but humans cannot perform it.

Some robots are programmed to complete obstacle courses. A robot does not necessarily "know" that it should not run into a wall. Rather a human has to program how the robot might react to its environment. A major point in this debate: is whether it is intelligent to be able to do something that has been done before or whether intelligence requires creativity.

2. Controlling Robots

There are different ways of controlling robots and each has advantages and disadvantages relative to the other control methods. Similarly, there is no single correct way of operating an unmanned vehicle; rather effective control depends on the mission that needs to be accomplished. Figure 6 shows a timeline projecting the relationship of human interaction compared to robot autonomy for unmanned vehicle control.

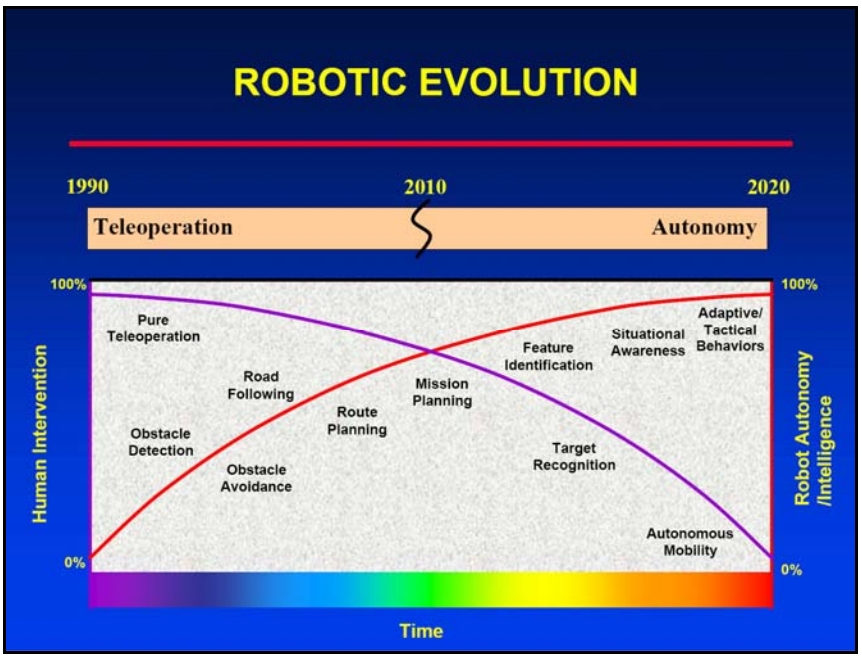

Figure 6. A timeline of projected advancement of autonomy in robots. Generally more intelligent a robot is, the less humans have to do to operate a robot. From (Department of Defense (DoD) Joint Robotics Program (JRP))

a. Remote Control (RC)

Remote control (RC) usually suggests the image of joystick control for a toy car or drone. Remote operation is the easiest to construct, but provides the least practical way to control a robot in military applications. The operator needs to maintain sight with the robot and its environment while controlling the robot. The operator can see if the robot ran into an obstacle and the user has a total situational picture on what is going on around the robot. However, the major drawback to this method is that the operator has to maintain visual reference with the robot. This is not always practical or possible in the real world. Sometimes robots operate in areas in which humans cannot go because the area is too small, too dangerous, or too far away. The major drawback of controlling robots by remote control is that it fails to remove the operator from danger.

b. Teleoperation

Teleoperation is the next step towards autonomy above remote control. "A teleoperator is a machine that extends a person's sensing and/or manipulating capability to a location remote from that person" (Sheridan 4). Teleoperation has been used in space, nuclear plants, toxic waste clean-up, construction, agriculture, mining, military operations, and even surgery. Teleoperation addresses the problem of the user still being in harms way that is associated with the use of remote control because the operator controls the robot through a robot's camera. Teleoperation creates some different problems that remote control does not have. However, the human is still in control of the robot, therefore the robot does not have to be programmed to do anything.

Teleoperation has some problems associated with it. Communications lag is an issue when there are large distances between the robot and the operator. Usually the farther the distance, the longer it will take to complete the task due to communications lag. For example, the round-trip delay for vehicles located in Earth's lower orbit is 0.4 seconds (Sheridan 123). Communications lag is not only a problem for space vehicles, but can affect underwater vehicles. Sound can travel approximately 1500 meters per second in water, which can cause significant communications lag depending on how deep the vehicle is operating and the current sound profile of the water. A typical cycle is that

the operator gives commands to the robot, the robot receives the command and then completes the task; however, the user has to make sure nothing unexpected occurs during this process (Murphy 31).

Operators are human and are more focused during the beginning of a mission, losing attentiveness during a long mission. Teleoperation can cause headaches and an operator might experience simulator sickness due to the visual perception of motion while the user vestibular system says the user is actually staying still (Murphy 31). One of the biggest challenges facing operators is maintaining both the robot's and their own real-world situational awareness. A focused operator might only be attentive to what the robot camera is pointed at. The operator does not know what is outside the robot's view, or if the robot is stuck on an object. Normally the camera on a robot has a narrower viewpoint than that of a human which can lead to poorer performance in tasks due to poor situational awareness. Some robots supervised by teleoperation requires up to five operators to control it (Murphy 31). The extra operators can be a hidden cost not considered during teleoperation design.

c. Partial or Full Autonomy

A robot that is partially or fully autonomous is the hardest level of control to achieve, but can offer the most capabilities. There are varying degrees of autonomy. At the low end, the robot is programmed not to run into things, but the human still controls the overall goals of the robot. At the other end of the autonomous spectrum, the robot is on its own and it makes decisions based on its program and the environment. The main problem with autonomy is programming the robot to robustly control itself to accomplish complex tasks. That is why autonomous vehicles do not perform some of the most complex tasks. As an example, it is easy to program a robot, which bounces arbitrarily off obstacles. However, it is difficult to program an unmanned surface vehicle so that it can operate following the navigational rules of the road. A fully autonomous vehicle that was programmed correctly hopefully allows humans to only supervise and control the robot when necessary. In the coming years robots will be doing jobs never thought possible. It will likely be hard for humans to trust robots to do anything fully autonomous that jeopardizes human life, such as firing a weapon or performing surgery.

3. Different Types of Autonomous Unmanned Vehicles (AUVs)

a. Unmanned Air Vehicles (UAVs)

UAVs operate in a medium that allows the vehicle to move quickly, and communication with the vehicle is easy because sensors have more range in the air than other mediums. UAV technology has matured faster than any other type of unmanned vehicles, likely because of extensive research regarding manned aircraft (National Academy of Sciences (NAS) Naval Studies Board 89). UAVs are small, can typically stay on station longer than traditional platforms, and can perform maneuvers that human pilots cannot handle. UAVs can be launched from either a ground station or a ship. Due to their size and mission length, UAVs have minimum impact on deck cycles of an aircraft carrier or other large deck ships (National Academy of Sciences (NAS) Naval Studies Board 90). The small size of UAVs can make it almost impossible for the enemy to know they are overhead, which in turn can enable UAVs to collect information that conventional platforms or satellites are unable to collect. For instance, a UAV might observe an insurgent who fired a weapon and then tries to blend into a crowd. A UAV with the right technology can follow that insurgent to his home base and then alert troops where to capture him.

b. Unmanned Surface Vehicles (USVs)

USVs are the newest type of unmanned vehicle, and its master plan still is unpublished. USVs can achieve high speeds, for example, the Owl USV has a maximum speed of 45 knots (National Academy of Sciences (NAS) Naval Studies Board 121). USVs can communicate easily with other vehicles, due to height-based line of sight restrictions to the horizon. The visual presence of an USV can aid in missions where deterrence is needed, such as harbor defense. Some USVs are semi-submersible vehicles like the Remote Mine-Hunting System, which can allow them to covertly complete missions like UUVs. USVs can be launched and recovered from a ship in a similar fashion to that of a Rigid Hull Inflatable Boat (RHIB). However, a significant limitation is storage requirements on ships. USVs typically need a storage area to protect their sensors and also to perform maintenance.

USVs also need to be able to operate in difficult traffic patterns in harbors. Currently USVs are not permitted to operate independently without human supervision due to the navigational rules of the road. Until that happens, USVs cannot operate without direct supervision.

c. Unmanned Underwater Vehicles (UUVs)

UUVs operate in the medium, which provides the most difficult control challenges. The operator is unable to see a robot underwater and it is also hard to communicate with the robot. This means that UUVs are the most autonomous of all the vehicles because of necessity. UUVs also have size limitations since they must be self-contained and self-sufficient. In order for UUVs to be utilized tactically by submarines, UUVs need the autonomy to be able to be recovered in a dry deck shelter, torpedo tube, or missile tube. Overall, size restrictions also put a limit on the power capacity and endurance of the robot.

Operating underwater gives UUVs multiple advantages. UUVs can operate in an area without anyone knowing about it. They are quiet because they run off batteries and small size makes them difficult to detect with sonar.

D. WHY UNMANNED VEHICLES ARE IMPORTANT

1. Dull, Dangerous, and Dirty

Robots are expected to perform missions that may not be desirable for humans to perform. Some missions that humans perform are dull such as long tedious missions. Other missions are dangerous for humans to perform like dealing with unexploded ordinance. The last area that robots are expected to perform missions in are dirty areas which means performing missions that are contaminated with threats like nuclear, biological, or chemical agents. However, robots today only serve as a tool for humans in these missions areas, and are not fully trusted to complete any mission without constant supervision. Having robots performing the dull, dangerous, and dirty jobs reduces the risk to human life.

2. Increasing Mission Areas for the Navy

The size of the armed forces has been on the decline since the end of the Cold War. The major threat facing the United States was believed to be gone with the collapse of the Soviet Union. Since the end of the Cold War, the threat of conventional warfare remains as exemplified by the first Gulf War and today the threat still exists with countries like North Korea, China, and Iran. Conventional warfare is not the only role expected from the armed forces. The armed forces are fighting the Global War on Terrorism (GWOT), conducting stability operations, and performing homeland defense ensuring that a future terrorist attack does not occur again on American soil. Asymmetric threats have risen since fighting the war on terrorism. Terrorists realize they cannot beat the U.S. with conventional means. Rather they use tactics like improvised explosive devices (IEDs), a weapon category that can also include sea mines. IEDs have the ability to hamper the United States' technological advantage. Unmanned vehicles can aid in completing the new mission areas for the Navy and help neutralize asymmetric threats.

3. Decreasing Size of the Navy

Even with the increase in mission areas, the size of the Navy has continued to be on the decline. Figure 7 shows an overall trend of decreasing personnel. This means less people have to complete more missions. Robots can help complete missions that are required by the Navy by helping to reduce the workload on each sailor. In 1987, the Navy had 587 ships, and in 2003, the Navy had 297 ships (O'Rourke, "Navy Ship Procurement" 1). However, there are plans to increase the size of the Navy. An earlier plan required the Navy to expand to 375 ships composed of 12 aircraft carriers, 55 attack submarines, 4 SSGNs, 104 cruisers, destroyers, and frigates, 56 LCSs, 37 amphibious ships, and the other 107 ships are mine hunters or supply ships (O'Rourke, "Navy Ship Procurement" 2). However, Admiral Mullen wants the Navy to be composed of 313 ships (Statement of Admiral Mike Mullen 2).

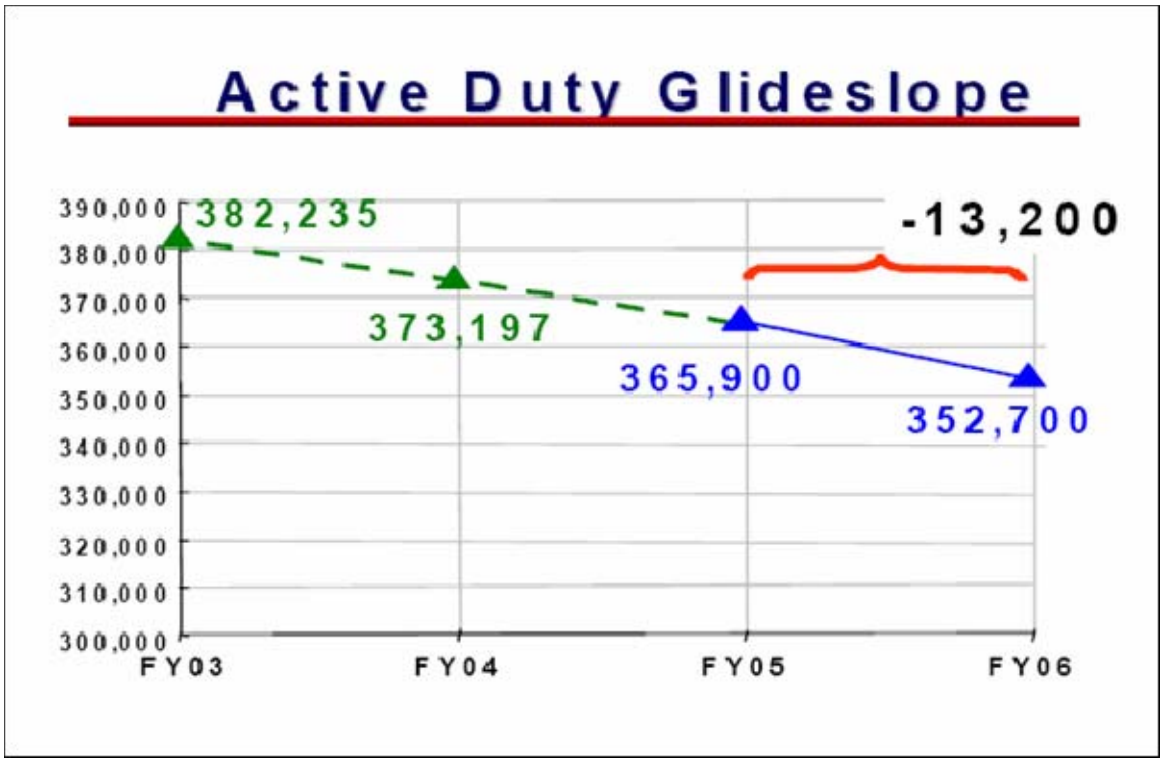

Figure 7. Navy personnel totals continue decrease. (Statement of Admiral Vern Clark, 2005)

4. Cost

The Navy is in a situation where there are more missions, but at the same time, there are fewer personnel to complete those missions. The missions that need to be completed are all around the globe. The solution for the Navy is not necessarily to simply build more ships, submarines, and airplanes. The problem with building more platforms is that the Navy in turn needs more personnel to operate and maintain those platforms. Thus building more platforms may not be the best way of utilizing a limited budget. Figure 8 illustrates how the cost of combat platforms has increased in the past three decades. For example, in 1967 an attack submarine (SSN) cost 484 million dollars while the new Virginia class sub in 2005 costs 2.427 billion dollars.

Figure 8. Combat platforms cost increased through the years. An attack sub, in 1967, cost 484 million dollars when adjusted for inflation. The new Virginia class submarine cost 2.427 billion dollars in 2005, an increase of 401%. (Statement of Admiral Vern Clark 2005)

One solution to the problem of more mission areas despite less manpower and increased cost of combat platforms is to find alternatives to conventional platforms. Robots can help solve those problems because they are relatively cheap and they do not greatly increase the need for manpower. In addition, robots can help make the combat platforms become more affective. However, some unmanned vehicles have hidden costs associated with them like having several pilots for one UAV (National Academy of Sciences (NAS) Naval Studies Board 96). Some other autonomous vehicles are cheap to purchase and one person can monitor multiple robots performing multiple missions at the same time, which reduces the operating cost of unmanned systems.

5. Blue Water and Brown Water

The Navy is evolving from solely supporting blue-water operations to supporting brown-water operations. In 2003, General Hagee and Admiral Clark wrote, “the role of the Navy and Marine Corps in the U.S. military is to provide credible, sustained combat power from the sea when and where it is needed” (National Academy of Sciences (NAS)

Naval Studies Board 20). This means moving from the deep blue ocean into the littorals. The littorals possess many dangers not faced in the deep ocean like mines, diesel submarines, swarms of small boats, anti-ship cruise missiles, shore batteries, and varying topography (National Academy of Sciences (NAS) Naval Studies Board). Such a change in strategic focus is not unique to the Navy. For example, future wars were once thought to be fought on the plains of Europe, but now urban warfare seems more likely.

The GWOT illustrates that there are more threats throughout the world than once thought, and new threats can rapidly arise that the Navy might not be ready to deal with. Unmanned vehicles enable the Navy to deal with future threats quickly because they are cheap enough that they can be updated and replaced more rapidly than conventional platforms. Conventional platforms such as ships, aircraft, and submarines have billions of dollars and over a decade of development invested in them. That makes conventional platforms hard to replace even though the mission it was designed for is no longer a major threat. Unmanned vehicles can allow for a more flexible response than from conventional platforms.

6. Increase of Combat Footprint

Most conventional platforms of the Navy are not designed for sustained missions in the littorals. Littoral topography and shoreline changes sustained might not have accurate information needed to operate a manned platform. Submarines, for example, have a difficult time operating in shallow water because of the possibility of hitting the bottom or exposing the submarine on the surface (Johnson 5). Unmanned vehicles can extend the operational range of submarines due to depth restrictions of certain areas. "Seventy-four percent of the Persian Gulf and sixty-three percent of the Yellow Sea are shallower than thirty fathoms, the use of UUVs could covertly extend the reach of the submarine in these cases by 100 and 200 nautical miles, respectively" (Johnson 5). Extending the combat footprint of any platform makes it a more affective war-fighting tool. A submarine operating multiple UUVs can then monitor multiple areas at one time, and simultaneously perform missions that might otherwise take multiple submarines to

complete. Figure 9 shows an increase in targets through the years. Unmanned vehicles can aid manned aircraft in handling the increase in targets

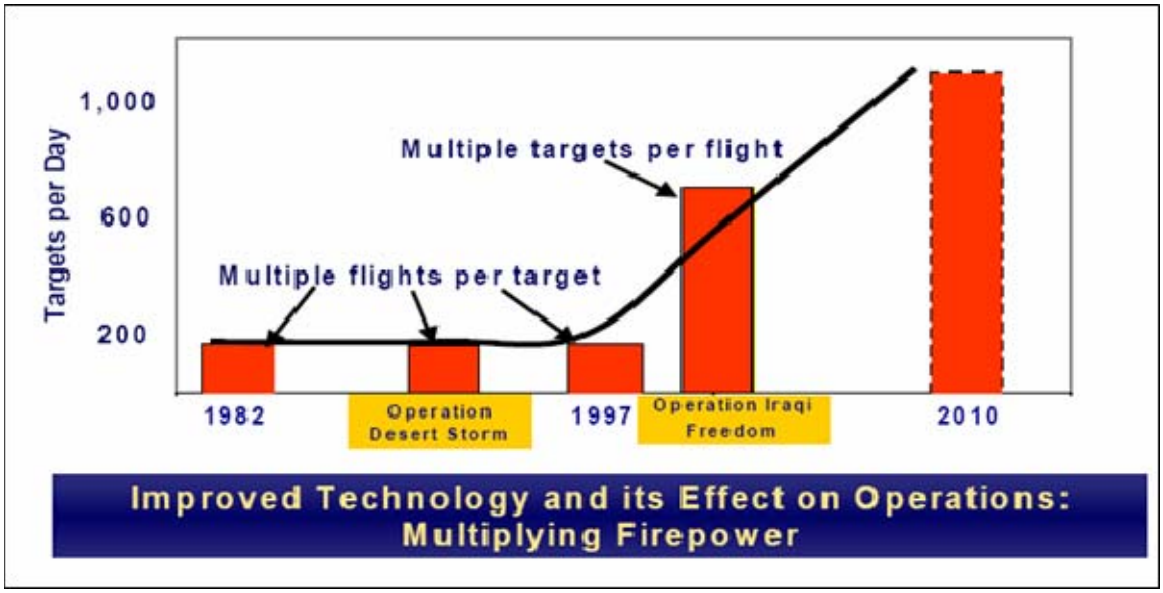

Figure 9. The number of targets per flight rises as aircraft technology increases. Robots can help human operators with the increase workload by identifying targets or even firing weapons at targets. (Statement of Admiral Vern Clark 2005)

E. SEAPOWER 21

Sea Power 21 is the guiding doctrine to govern how the Navy is supposed to fight in the future. Admiral Clark, a former, Chief of Naval Operations (CNO), developed Sea Power 21 in 2002, and this strategy was subsequently reaffirmed by his successor, Admiral Mullen. Sea Power 21 is broken down into four parts: Sea Shield, Sea Basing, Sea Strike, and FORCEnet.

1. Sea Shield

The traditional role of the Navy is to protect the area where operations are taking place. If Marines are landing on a beach, the Navy's job is to ensure a safe passage from the ships to the beach. However, the Navy in the past could not protect areas that the Navy was not operating in. The technology did not exist to monitor the entire battlespace environment. The threat of terrorism has shown that a threat can come from any corner of the globe. The Navy has to protect both forward operating areas as well as the nation as a whole at the same time. The Navy defense plan had to change its scope from the

tactical level to the strategic level. "Sea Shield will protect our national interests with layered global defensive power based on control of the seas, forward presence, and networked intelligence" (Clark). Sea Shield will have an impact on the following areas: project defense for joint forces and allies ashore; sustain access for maritime trade, coalition building, and military operations; extend homeland defense via forward presence and networked intelligence; and enhanced international stability, security, and engagement (Clark).

In order to ensure that Sea Shield is a successful strategy the Navy has to implement certain measures. The Navy has to "expand combat reach, deploy theater missile defense as soon as possible, create common operational pictures for air, surface, and subsurface forces, accelerate the development of sea-based unmanned vehicles to operate in every environment, and invest in self-defense capabilities to ensure sea superiority" (Clark). For Sea Shield to be effective, information needs to be shared from aircraft, ships, submarines, and unmanned vehicles. This will help increase situational awareness. However, too much unprocessed information being collected and passed can allow some important information to be lost. Ideally, if an unmanned sensor detects a possible threat, like a small boat entering a restricted area, the unmanned vehicle can alert a patrol boat to investigate the possible threat. If an unmanned vehicle also notifies the patrol boat every time the air temperature changes the patrol craft may simply ignore all notifications.

The threat of terrorism makes Sea Shield an essential strategy for the Navy. Preventing another attack on US soil is critical due to risk of the proliferation of weapons of mass destruction. Sea Shield not only provides homeland defense, but protects foreword deployed units. "The importance of Sea Shield to our nation has never been greater, as the proliferation of advance weapons and asymmetric attack techniques places an increasing premium on the value of deterrence and battle space dominance. Sea Shield capabilities, deployed forward, will help dissuade aggressors before the onset of conflict" (Clark).

SEA SHIELD
• Project layered, defensive power -- globally
• Extend homeland security with networked intelligence & global reach
• Sustain access via littoral dominance
• Protect joint forces and allies ashore
• Extend defensive umbrella deep inland
• Strengthen strategic stability
• Provide operational security
Sea Shield
Projecting Defensive Assurance...
assure allies, deter adversaries, sustain access

Figure 10. Sea Shield objectives (Statement of Admiral Vern Clark 2005)

2. Sea Basing

The ability to maneuver has always been important in warfare. The supply line has always constrained the ability to move. The modern naval supply line is more complex than ever before because of the extent of naval operations throughout the world. Sea Basing will allow successful missions in remote parts of the world. In order for Sea Basing to be successful, supplies and equipment need to be strategically deployed, the United States needs to form an international coalition to help achieve a supply network, and operations need to utilize these short supply lines (Clark).

SEA BASING
• Sea-bases key joint warfighting capabilities
• Offensive & defensive power projection
• Command & control
• Logistics
• Extends naval advantages to the joint team
• Freedom of operations
• Immediate employability
• Increased security
• Sustained access
• 100% of the earth's surface as joint maneuver space
Sea Basing
Projecting Operational Independence…
joint power from the sea

Figure 11. Sea basing objectives (Statement of Admiral Vern Clark 2005)

3. Sea Strike

Projecting force onto land has always been a mission goal for navies throughout history. The U.S. Navy can project force onto land by landing Marines, firing Tomahawk missiles, or through aircraft. Being able to project power onto land is one part of the equation. Knowing where to attack is the other part of the equation. In the modern era of warfare, smart weapons can be placed at a precise location. Targets that need to be taken out are sometimes located next to civilian areas like a hospital or marketplace. Terrorists live among innocent citizens and it is important not to kill innocent lives. In order to win the Global War on Terrorism, it does not matter how many terrorists are killed, but rather winning over the hearts and minds of the people. One way to win over the people is to prevent the loss of innocent lives when taking out terrorist locations. UAVs have the ability to perform reconnaissance on a target before a strike to ensure that the target matches the intelligence and to help determine what type of ordnance needs to be used. UAVs can target a location with a laser which can be more precise than GPS.

SEA STRIKE
• Dominant & decisive power from the international domain
• Focused Effects: Precision strike, information operations, fires, covert strike, Special Operations Forces, and Marines
• Enabled by networked Intelligence, Surveillance & Reconnaissance (ISR) for knowledge superiority
• Seize the initiative
• Disrupt enemy timelines
•Preempt adversary options
•Ensure operational success
Sea Strike
Projecting Offensive Power…
responsive, precise, and persistent

Figure 12. Sea Strike is the offensive sub-pillar of Sea Power 21 (Statement of Admiral Vern Clark 2005)

4. ForceNet

ForceNet is the most important concept in Sea Power 21. ForceNet objective is to share information between sailors, sensors, platforms, and weapons in order to insure victory (Clark). Giving decision makers real-time information will allow for quicker and more accurate decisions. More information being shared will allow for a common tactical picture, which will increase situational awareness. With the increase of unmanned vehicles, conducting ISR missions will also increase the amount of information available to the war fighter. However, the increase of data could easily overwhelm human decision makers. Software like the AUVW needs to alert users when important things happen like if an unmanned vehicle detects a new enemy contact. Without ForceNet-based capabilities, the Sea Strike, Sea Shield, and Sea Basing strategies are as affective.

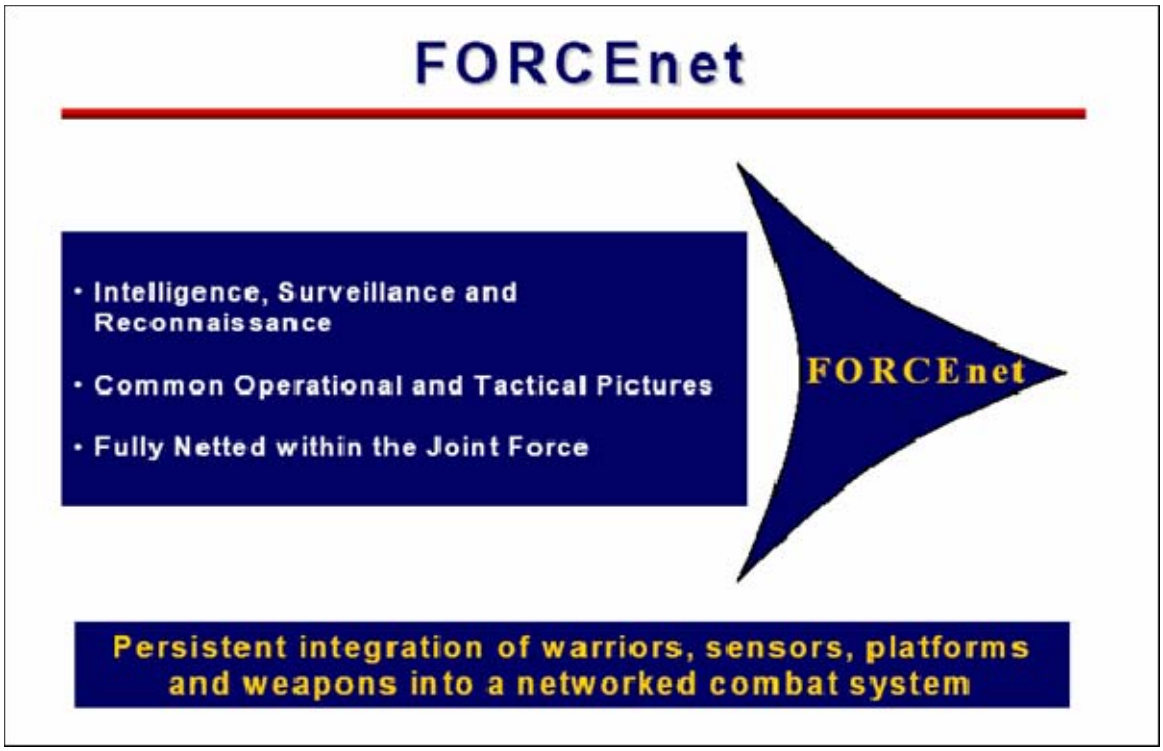
FORCEnet
• Intelligence, Surveillance and Reconnaissance
• Common Operational and Tactical Pictures
• Fully Netted within the Joint Force
FORCEnet
Persistent integration of warriors, sensors, platforms and weapons into a networked combat system

Figure 13. FORCEnet is the communications network sub-pillar of Sea Power 21 (Statement of Admiral Vern Clark 2005)

F. THOUSAND SHIP NAVY

Admiral Mike Mullen's, the current CNO, strategic idea is the Thousand Ship Navy. The motivation for this idea is that the ports of the United States of America are wide open to attack from weapons of mass destruction. Over eleven million cargo containers enter this country each year and containers move over ninety percent of the world's cargo (U.S. Customs and Border Protection 12). Only a small percentage of containers that enter and leave the country can be inspected with current technology. Even the exact origin of the container is unknown. This exposes the US to unknown risks from unknown enemies. The US is not the only country in the world facing this threat. Countries need to share information on cargo ships' origins and aid other countries when needed. The Thousand Ship Navy expands the idea of Sea Shield through the international community by using principles found in FORCEnet.

The Thousand Ship Navy is not about having a thousand-ship Navy. Rather it is a metaphor for an international cooperation to build "a global network of maritime nations

for a free and secure maritime domain" from irregular and unrestricted warfare (Mullen). The threat faced by one nation affects every nation. An example of this is pirates because they have ties to "international criminal networks, smuggling of hazardous cargoes, and disruption of vital commerce" which can affect the fragile global economy (Mullen). The Thousand Ship Navy requires the US Navy to be both a war fighting organization but also to take on the role of a security force. No matter how large the US Navy is it cannot do, the job alone because there are too many threats and the world is too big for the Navy to perform alone. The Navy needs to work with the Coast Guard to help monitor US water. In addition, it takes a coalition of countries, who share the idea of security and prosperity, to work together. Unmanned vehicles will aid this coalition in tracking ships in remote parts of the world. This effort is to prevent terrorist and pirate attacks on any country or port because of the affects on that country and the economy of the world. For example, "detonation of a weapon of mass destruction or weapon of mass effect at a U.S. port of entry could cause a $1 trillion disruption" to the US economy (U.S. Customs and Border Protection 22). That does not include the affects on the world's economy. An international coalition would provide global security that countries by themselves cannot achieve.

G. SUMMARY

This chapter first covered future combat platforms that the Navy will be acquiring in the near future and how unmanned vehicles will help accomplish their missions. The background information on robots was introduced. The chapter then explains the current status of the Navy and why unmanned vehicles will be an asset to the Navy. Finally, the strategic plans of Sea Power 21 and the Thousand Ship Navy, illustrates how unmanned vehicles are needed to accomplish future plans of the Navy.

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IV. AUTHORITATIVE GUIDANCE AND STRATEGIC PLANNING FOR NAVY AUVS

A. INTRODUCTION

There are multiple diverse sources that give guidance on what is expected from unmanned vehicles. These reports are published from authoritative offices like the Secretary of Defense and Department of the Navy. These reports are typically not classified and can be accessed through the web. In developing an application like AUVW, it is important to know what missions are expected from AUVs in the future. The purpose of this chapter is to outline the missions set forth in the various master plans. Those future requirements can then be used to guide future AUVW development.

B. AUTONOMOUS VEHICLES IN SUPPORT OF NAVAL OPERATIONS

This publication provides a broad overview of unmanned vehicles. One of the major areas that this document addresses is current vehicles and their capabilities. After introducing various types of vehicles, it lists the current mission areas outlined by their respective master plans or from other sources. The final area that this document touches upon is technology issues facing each type of vehicle. This document is one of the few documents that explain the future mission areas for USVs.

C. UUV MASTER PLAN

The UUV master plan details which missions are to be accomplished and why those missions are important. This document should be the roadmap in helping develop capabilities for supporting control stations like the AUVW. The following missions are listed in order of priority for UUVs to accomplish.

1. Intelligence, Surveillance and Reconnaissance (ISR)

UUVs can collect information that no other platform can. In the modern warfare era, information is essential in winning the battle. UUVs can collect information both above and below the surface of the ocean while the enemy is unaware of its presence. In addition, UUVs can stay on station longer than any manned platform and access areas

denied to conventional platforms. "UUV capabilities would include persistent littoral ISR, harbor or port monitoring, chemical, biological, nuclear, radiological, explosives detection and localization, surveillance sensor emplacement, battle damage assessment, active target designation, and launch and coordination of UAVs" (Department of the Navy (DON) 20).

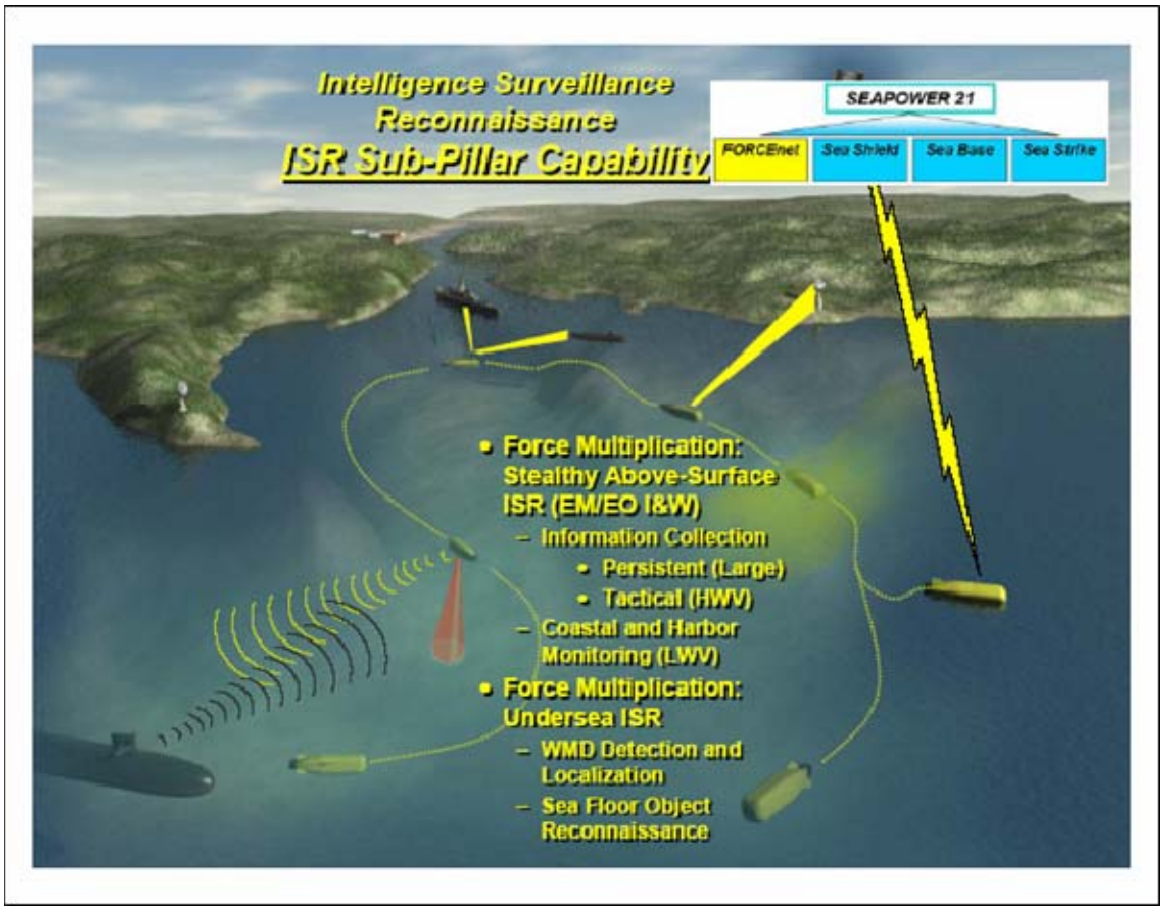

Figure 14. ISR is the most important mission outlined by the UUV master plan. ISR goal is to collect information (Department of the Navy (DON))

2. Mine Countermeasures (MCM)

To clear a minefield without UUVs requires mine-clearing ships to search the designated area. This exposes ships and its crew to the danger of mines. Clearing a minefield with conventional ships alert the enemy that there is going to be naval activity in that area, thus ruining any element of surprise. Losing the element of

surprise can cost lives especially in amphibious operations. UUVs can provide a means to covertly remove an area of mines.

UUVs also have the advantage over traditional mine hunters because UUVs are easily transportable. The Navy mine-clearers are slow and can take a long time to transient across oceans and sometimes are carried on heavy-lift transports. However, an UUV like REMUS could be put in an aircraft and flown anywhere in the world in a matter of hours rather than days like with mine-clearing ships.

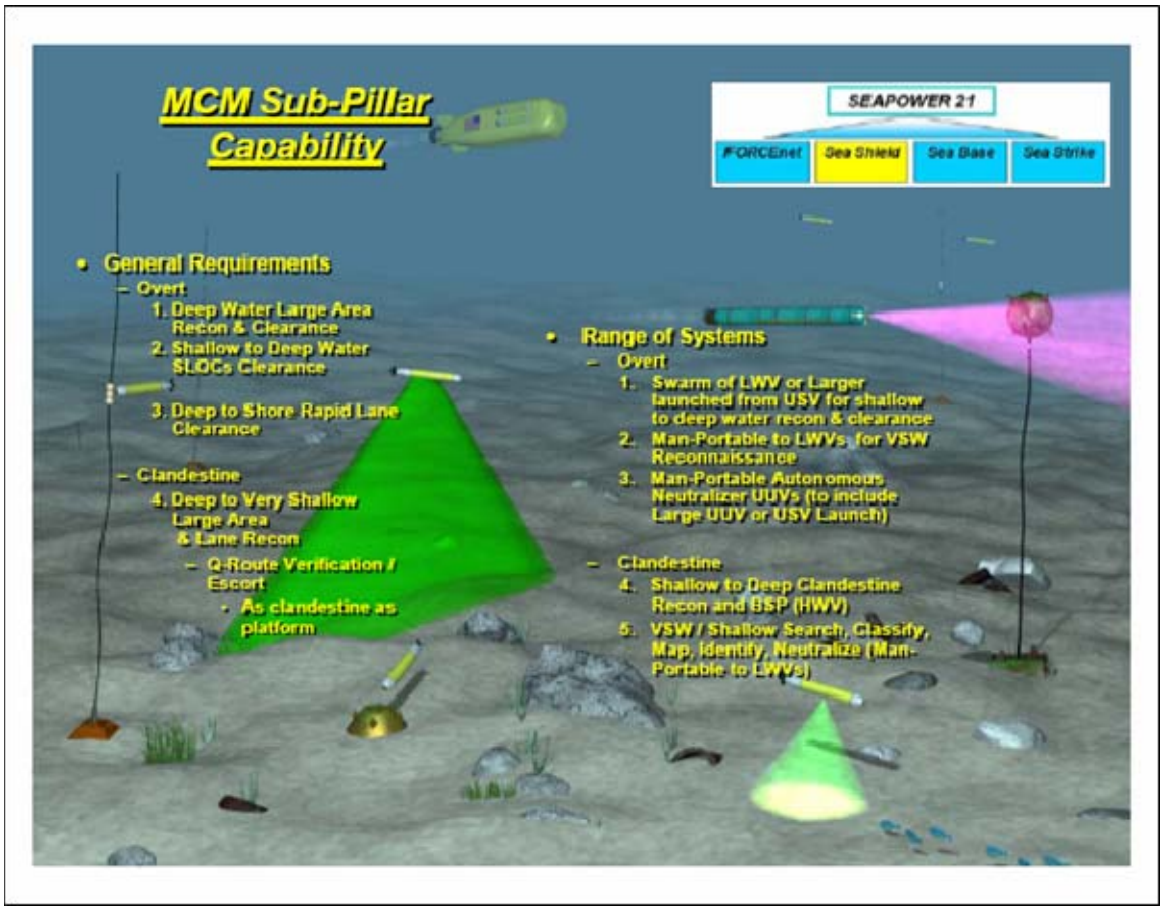
MCM Sub-Pillar Capability
SEAPOWER 21
FORCEnet
Sea Shield
Sea Base
Sea Strike
• General Requirements
– Overt
1. Deep Water Large Area Recon & Clearance
2. Shallow to Deep Water SLOCs Clearance
3. Deep to Shore Rapid Lane Clearance
– Clandestine
4. Deep to Very Shallow Large Area & Lane Recon
– Q-Route Verification / Escort
- As clandestine as platform
• Range of Systems
– Overt
1. Swarm of LWV or Larger launched from USV for shallow to deep water recon & clearance
2. Man-Portable to LWVs for VSW Reconnaissance
3. Man-Portable Autonomous Neutralizer UUVs (to include Large UUV or USV Launch)
– Clandestine
4. Shallow to Deep Clandestine Recon and BSP (HWV)
5. VSW / Shallow Search, Classify, Map, Identify, Neutralize (Man-Portable to LWVs)

Figure 15. MCM goal is to eliminate mines in operational areas. from (Department of the Navy (DON))

3. Anti-Submarine Warfare (ASW)

Submarines still remain hard to find and with out knowing where an enemy submarine is at all times can allow the enemy sub to operate in areas without knowing

about it. “The objective of this capability is to patrol, detect, track, and hand off adversary submarines to U.S. Forces using UUVs (Department of the Navy (DON) 31). Opposing submarines have an advantage over U.S. submarines because they are smaller, some are diesel powered and while submerged are very quiet, and with local knowledge are able to hide and evade U.S. submarines” (Department of the Navy (DON) 32). UUVs could help eliminate this issue.

There are two types of ASW missions. The first one is hold at risk. The goal of this mission is to “deny enemy submarines an offensive capability by maintaining the ability to destroy them, if and when required, at a time and place of our choosing” (Task Force ASW 2). The second mission is called secure maneuver area. This mission is to “drive away or destroy enemy submarines, thereby protecting maritime operating areas” (Task Force ASW 3). Figure 16 illustrates the two different types of missions of ASW.

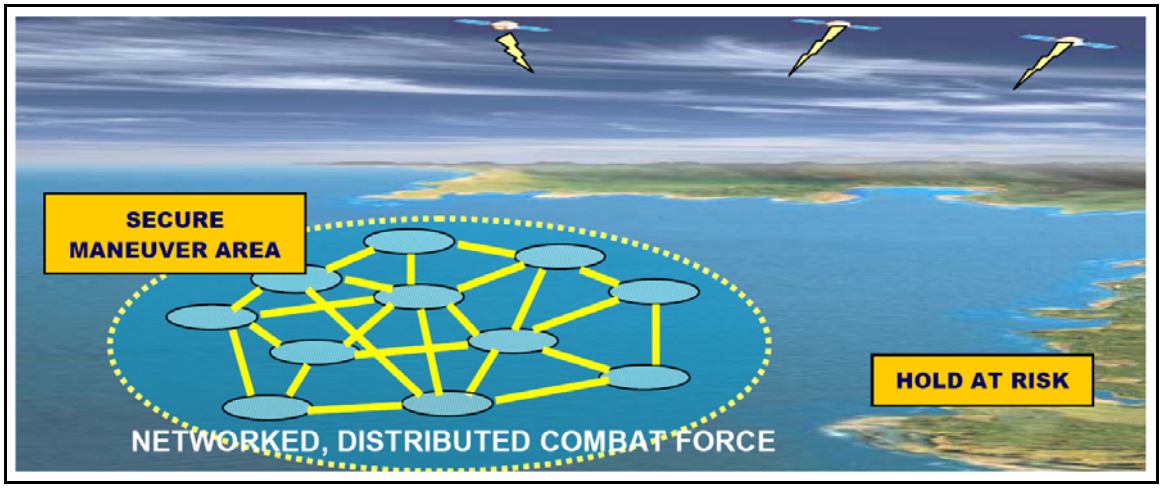

Figure 16. ASW is composed of two types of missions: hold at risk and secure maneuver area. Hold at risk focuses on keeping enemy subs from gaining access to the sea. While secure maneuver area is protecting an area of naval operations. (Task Force ASW 3).

UUVs perform hold at risk missions while other unmanned vehicles like USVs perform the secure maneuver area due to UUVs performance limitations. UUVs can enter into a harbor and follow a certain submarine or the UUV can move into a choke

point and wait for a submarine (Johnson 20). In the future, UUVs will detect and neutralize opposing submarines. Figure 17 highlights the concept of operations for the hold at risk mission.

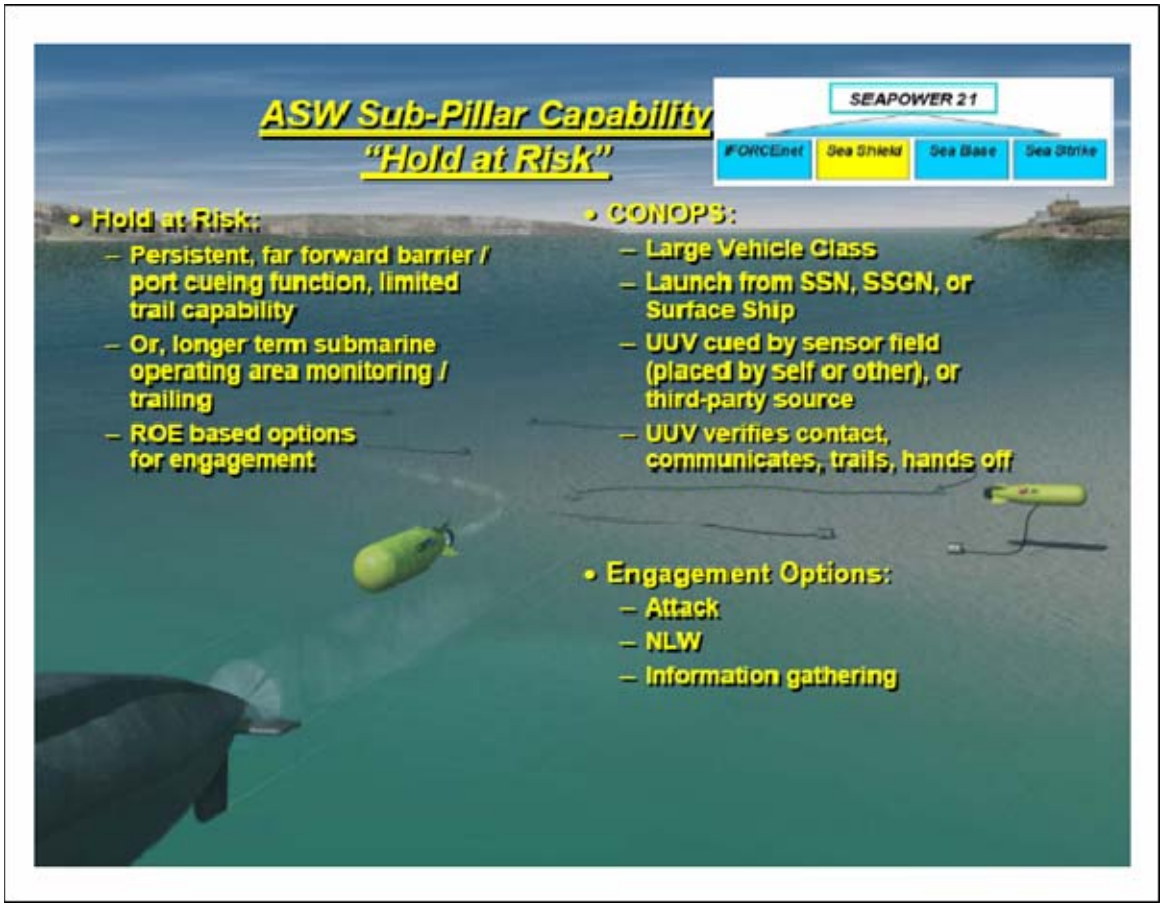
ASW Sub-Pillar Capability
"Hold at Risk"
SEAPOWER 21
FORCEnet
Sea Shield
Sea Base
Sea Strike
• Hold at Risk:
– Persistent, far forward barrier / port cueing function, limited trail capability
– Or, longer term submarine operating area monitoring / trailing
– ROE based options for engagement
• CONOPS:
– Large Vehicle Class
– Launch from SSN, SSGN, or Surface Ship
– UUV cued by sensor field (placed by self or other), or third-party source
– UUV verifies contact, communicates, trails, hands off
• Engagement Options:
– Attack
– NLW
– Information gathering

Figure 17. The Hold at Risk mission definition and concept of operations. from (Department of the Navy (DON))

4. Inspection/Identification (ID)

A major threat against a port is a terrorist attack. Terrorists can attack a port by swimming into a port to a ship of a high value like an aircraft carrier and place explosives on its hull. Besides naval ships, other targets of opportunity include bridges or piers. Both home and foreign ports that host Navy ships have this threat. Currently, divers perform the inspection/identification mission to reduce this threat.

Inspection/Identification mission area is in direct support of Homeland Defense and Anti-Terrorism/Force Protection (AT/FP). To accomplish this mission UUVs must be able to search piers, hulls of ships, and bottoms of berthing areas for unexploded ordnance and other foreign objects (Department of the Navy (DON) 35). Currently, divers or remote operated vehicles have to perform this task because of the visual identification needed. However, there are not enough divers to perform the searches since September 11, 2001, and it takes several hours to make a ship safe for a diver to search (Department of the Navy (DON) 13). This job is dangerous for a human to perform because of what might be discovered, and drivers swimming in dangerous water with ships operating in close proximity. UUVs need to develop better visual identification to be able to perform this mission.

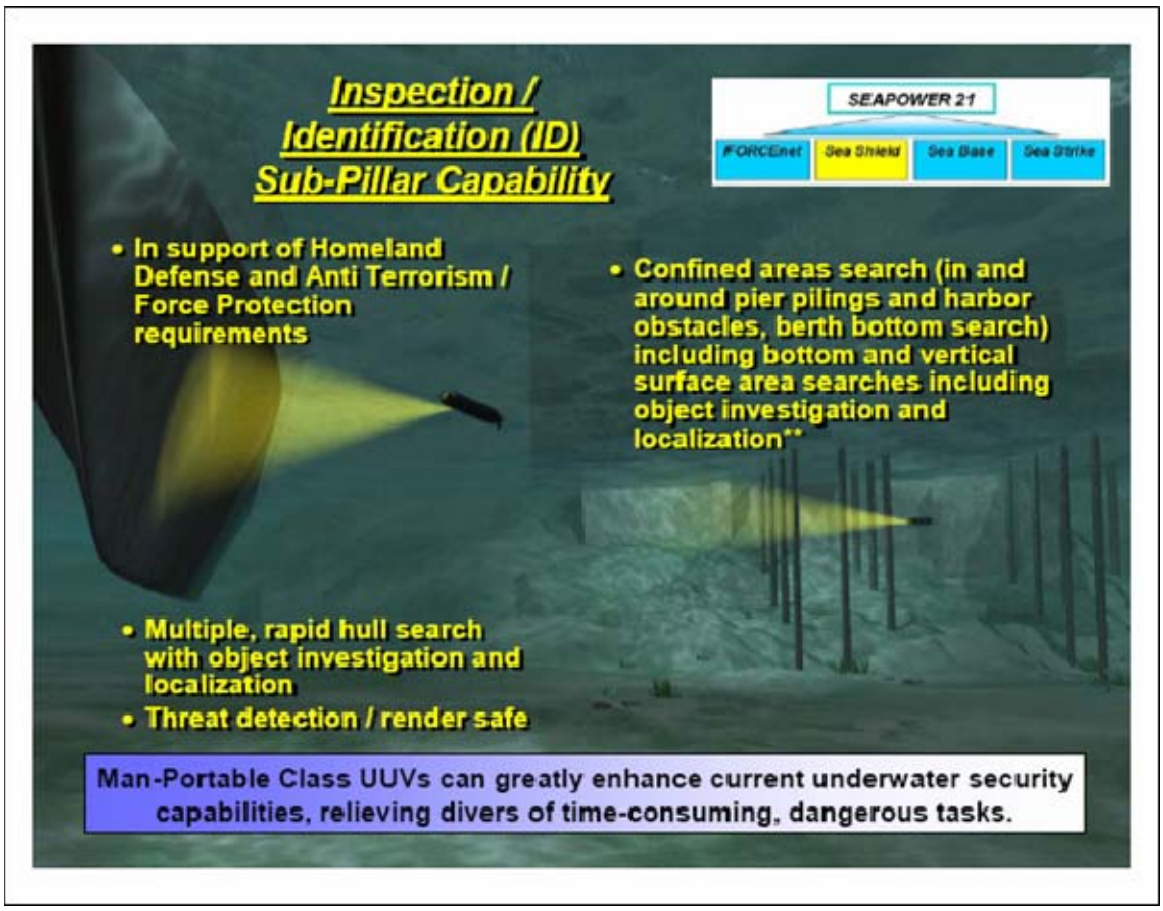
Inspection / Identification (ID) Sub-Pillar Capability
SEAPOWER 21
FORCEnet
Sea Shield
Sea Base
Sea Strike
• In support of Homeland Defense and Anti Terrorism / Force Protection requirements
• Confined areas search (in and around pier pilings and harbor obstacles, berth bottom search) including bottom and vertical surface area searches including object investigation and localization**
• Multiple, rapid hull search with object investigation and localization
• Threat detection / render safe
Man-Portable Class UUVs can greatly enhance current underwater security capabilities, relieving divers of time-consuming, dangerous tasks.

Figure 18. Inspection/ID Capabilities from (Department of the Navy (DON))

5. Oceanography

Knowing the environment is key in gaining the advantage over the enemy especially an environment as dynamic as the ocean. Currently oceanographic data is gathered from hull mounted or towed sensors. Gathering this data requires a ship to continually gather data to be of tactical use. This data is only for the area directly around the ship. UUVs can provide environmental data continuously without man hours being spent on this low intensity mission. Also, UUVs can collect data in the shallowest waters. "Data collected will support stringent navigation quality chart production and oceanographic data collection requirements, and also will be used to support ASW, SOF, Expeditionary Warfare (EXW), Ship to Objective Maneuver (STOM), and Mine Warfare (MIW) change detection" (Department of the Navy (DON) 41). UUVs collect data like bathymetry, current direction, saliently, temperature, density, the presence of bioluminescent organisms, and other important environmental data. Knowing this type of information is important to planning missions. For example, a SEAL team trying to sneak onto a beach at night may be seen by the enemy because of bioluminescent organisms giving away their location.

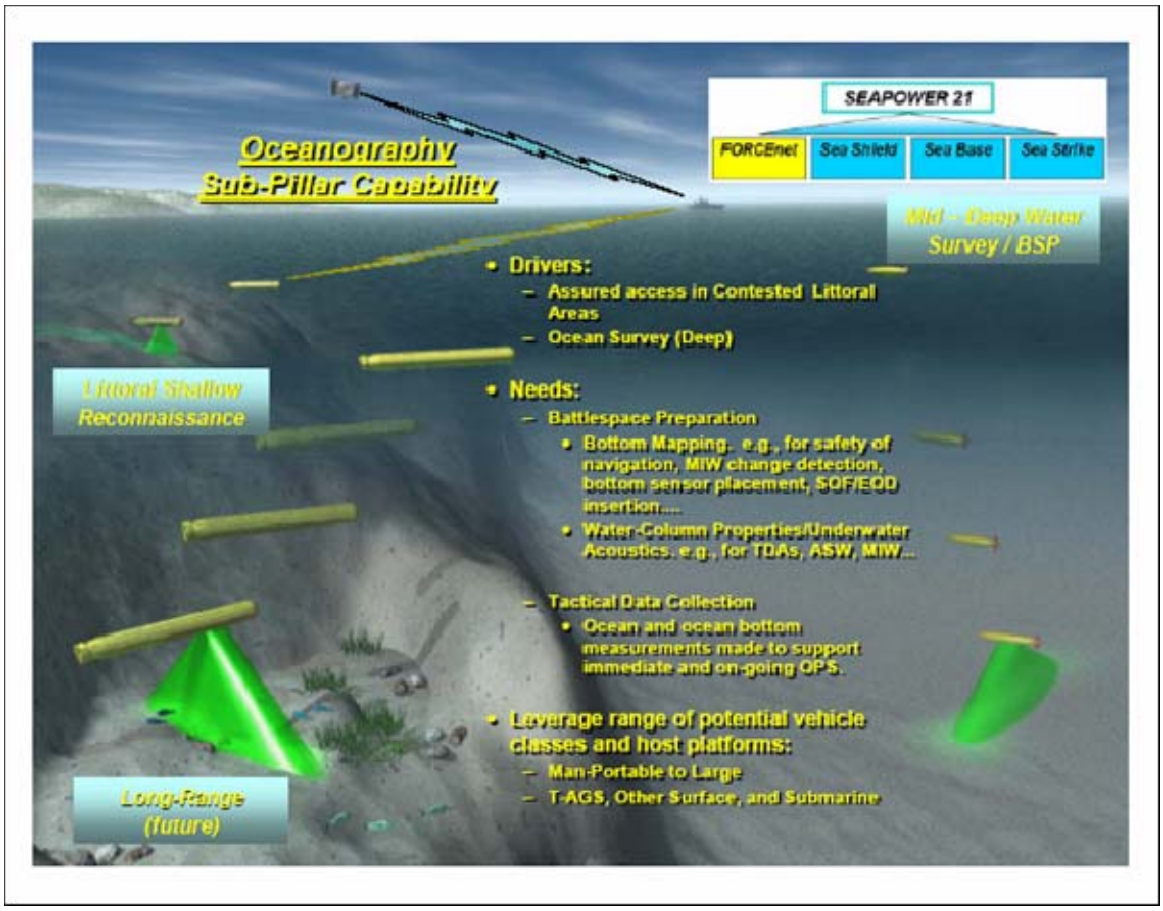
Oceanography
Sub-Pillar Capability
SEAPOWER 21
FORCEnet
Sea Shield
Sea Base
Sea Strike
Mid – Deep Water
Survey / BSP
• Drivers:
– Assured access in Contested Littoral Areas
– Ocean Survey (Deep)
Littoral Shallow
Reconnaissance
• Needs:
– Battlespace Preparation
• Bottom Mapping, e.g., for safety of navigation, MIW change detection, bottom sensor placement, SOF/EOD insertion....
• Water-Column Properties/Underwater Acoustics, e.g., for TDAs, ASW, MIW...
– Tactical Data Collection
• Ocean and ocean bottom measurements made to support immediate and on-going OPS.
• Leverage range of potential vehicle classes and host platforms:
– Man-Portable to Large
– T-AGS, Other Surface, and Submarine
Long-Range
(future)

Figure 19. Oceanography Capabilities from (Department of the Navy (DON))

6. Communications/Navigation Network Node (CN3)

CN3 falls under the FORCEnet sub pillar of Sea Power 21. This mission area is important in order to complete other missions. Communicating with vessels at sea is critical and vital in completing FORCEnet. Communication in the modern battlefield is important in achieving victory. Submarine captains use to have total autonomy over their boat, but lack real time knowledge about the world. However, with improved communications submarines can know what is going on and where it is important to operate.

One solution is to make a wired network underwater. However, a wired network is vulnerable to the enemy tapping the communications lines or fishermen trawling the area of the network. A wireless network of unmanned nodes is more secure than a wired network, but is a lot slower because the sound has to travel through the water. The

network could be used to communicate with SEAL delivery vehicles from launch to the shore or with submarines operating in the area. The submarine can remain at operating depth and speed without having to ascend to periscope depth. The network can also aide in navigation. This can be helpful for Special Forces trying to navigate to the correct beach.

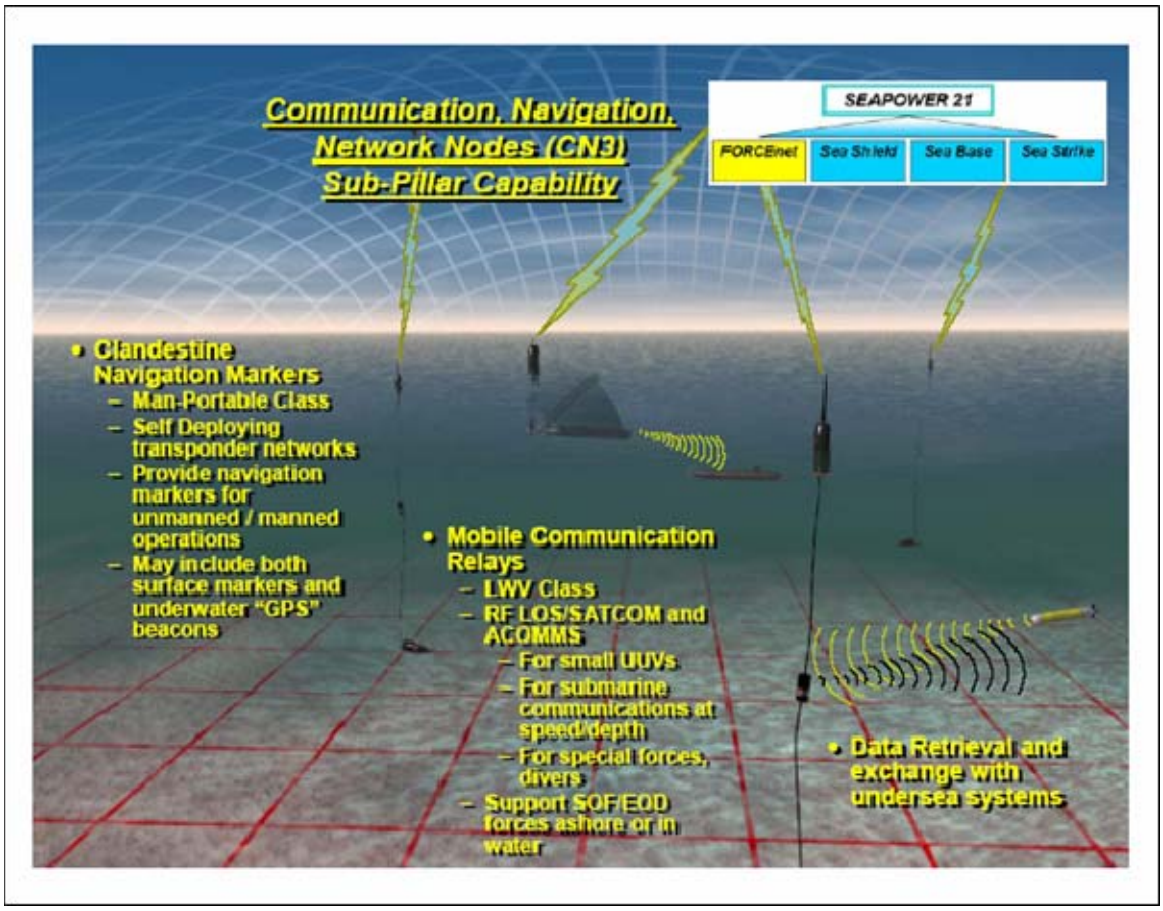
Communication, Navigation, Network Nodes (CN3) Sub-Pillar Capability
SEAPOWER 21
FORCEnet
Sea Shield
Sea Base
Sea Strike
• Clandestine Navigation Markers
– Man-Portable Class
– Self Deploying transponder networks
– Provide navigation markers for unmanned / manned operations
– May include both surface markers and underwater "GPS" beacons
• Mobile Communication Relays
– LWV Class
– RF LOS/SATCOM and ACOMMS
– For small UUVs
– For submarine communications at speed/depth
– For special forces, divers
– Support SOF/EOD forces ashore or in water
• Data Retrieval and exchange with undersea systems

Figure 20. CN3 Capabilities from (Department of the Navy (DON))

7. Payload Delivery

Payload delivery is the only mission for UUVs that fall under the Sea Basing sub pillar of Sea Power 21. Currently, UUVs have the capability to complete this mission. Therefore, payload delivery is not a top priority mission area.

Payload delivery is a support mission for other mission areas. It is critical to have the correct assets at the correct location at the right time in order to complete a mission.

"The UUV would provide the energy, navigation, autonomy, and payload deployment systems necessary to support the other missions" (Department of the Navy (DON) 47). Payload delivery can support the other mission areas which include MCM, Oceanography, ASW, CN3, SOF support, and time critical strike (Department of the Navy (DON) 48).

Payload Delivery
Sub-Pillar Capability
SEAPOWER 21
FORCEnet
Sea Shield
Sea Base
Sea Strike
• Large Class UUV delivers payloads in support of ASW, MIW, Comm/Nav Network Nodes, SOF/EOD, and Time Critical Strike
– Potential Payloads
– ASW Sensors
– Neutralization Devices
– Offensive Mines
– CN3 components
– TCS Weapons
– SOF weapons & supply cache
– Smaller UUVs, UAVs, UGVs
– Notional Requirements:
– Volume: 10's - 100's cubic feet
– Range: 10's - 100's nmi
– Speed: <10 knots
– Nav. Accuracy: 10's of feet

Figure 21. Payload Delivery Capability from (Department of the Navy (DON))

8. Information Operations (IO)

IO missions are considered part of the Sea Strike sub pillar of Sea Power 21. However, UUVs have not developed the sophisticated autonomy to complete this mission. This is why this is a lower priority mission for UUVs.

"The objective of Information Operations is to 'deceive, deter and disrupt our enemies'" (Department of the Navy (DON) 48). UUVs can perform either as a

submarine decoy or as a computer node jammer (Department of the Navy (DON) 48). Since UUVs can operate close to shore, they can project more power to jam the enemy sensors. Deceiving the enemy acts as a force multiplier. Enemy radar can be neutralized and the enemy could be deceived on where an attack will occur.

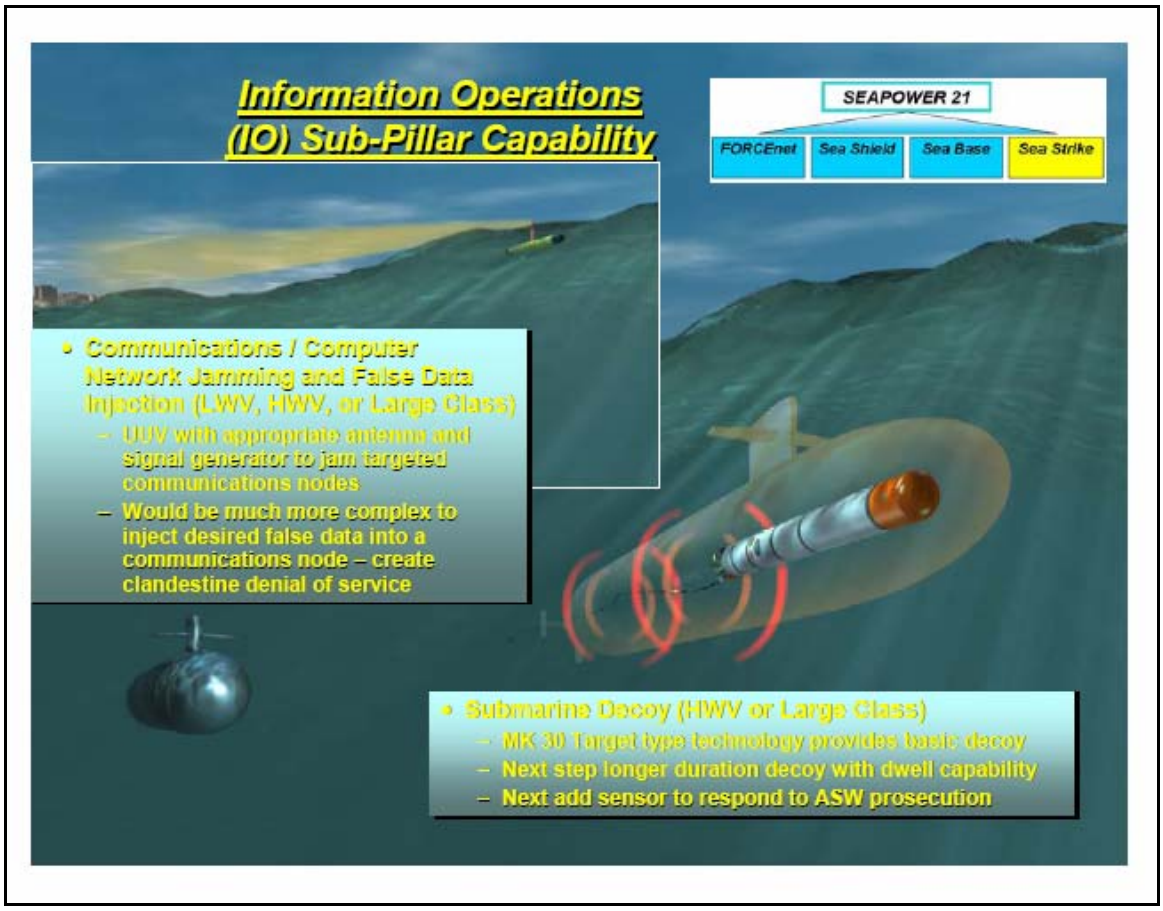
Information Operations
(IO) Sub-Pillar Capability
SEAPOWER 21
FORCEnet
Sea Shield
Sea Base
Sea Strike
• Communications / Computer Network Jamming and False Data Injection (LWV, HWV, or Large Class)
– UUV with appropriate antenna and signal generator to jam targeted communications nodes
– Would be much more complex to inject desired false data into a communications node – create clandestine denial of service
• Submarine Decoy (HWV or Large Class)
– MK 30 Target type technology provides basic decoy
– Next step longer duration decoy with dwell capability
– Next add sensor to respond to ASW prosecution

Figure 22. IO Capability from the (Department of the Navy (DON))

9. Time Critical Strike (TCS)

Time critical strike is the mission area with the least priority. An unmanned vehicle does not yet have the trust from humans to be able launch weapons because of the value of human life and the political repercussions if an unmanned vehicle launches a weapon at the wrong target. The time critical strike falls under the Sea Strike component of Sea Power 21.

UUVs have the advantage over manned platforms because they can operate close to the shore. Being close to shore allows UUVs to launch their ordnance and hit the target in seconds rather than minutes compared to manned platforms (Department of the Navy (DON) xii). UUVs can operate in an area for long periods of time without the enemy realizing they are there. Then they are able to strike when the enemy least expects it.

Figure 23. TCS Capability from (Department of the Navy (DON))

D. UAV MASTER PLAN

The UAV master plan, also known as the *Unmanned Aircraft Systems Roadmap 2005-2030*, is a joint document from the Office of the Secretary of Defense (OSD). The roadmap lists the missions that the Department of Defense (DoD) will focus on for the next two and half decades. However, UAVs can accomplish any mission that manned

aircraft is able to accomplish. The following table lists the mission areas for the different types of UAVs and the relative priority within those mission areas.

Mission	Small	Tactical	Theater	Combat
Reconnaissance	1	1	1	1
Signals Intel	10	3	2	5
Mine Detection/CM	7	11	13	14
Precision Target Location and Designation	2	2	3	2
Battle Management	4	10	4	7
Chem/Bio Reconnaissance	3	7	6	9
Counter Cam/Con/Deception	8	5	7	11
Electronic Warfare	14	9	10	4
Combat SAR	6	8	8	10
Communications/Data Relay	5	6	5	8
Information Warfare	15	12	11	6
Digital Mapping	11	13	9	12
Littoral Undersea Warfare	17	15	14	13
SOF Team Resupply	9	16	17	16
Weaponization/Strike	16	4	12	3
GPS Psuedolite	18	18	15	18
Covert Sensor Insertion	12	14	16	15
Decoy/Pathfinder	13	17	18	17

Table 3. Prioritized projection of mission requirements for different classes of UAVs are expected to perform. (Office of the Secretary of Defense 43)

Even though a UAV can accomplish a wide variety of missions, the UAV master plan outlines five broad mission areas. The five missions are ISR, strike/suppression of enemy air defense, destruction of enemy air defense, electronic attack, network node/relay, and aerial delivery/resupply. These five mission areas cover the majority of the missions outlined in Table 1.

1. ISR

Reconnaissance is one of the most important missions for any unmanned vehicle. The information gathered assists troops on the ground with planning operations. There are three categories of ISR missions for UAVs which are stand-off, over flight, and denied access (Office of the Secretary of Defense A2). Stand-off missions allow the United States to conduct reconnaissance missions, while respecting the airspace of sovereign nations, while over-flight missions are missions where the vehicle enters sovereign air space of another nation with (or without) permission (Office of the Secretary of Defense A2). Denied missions are similar to over-flight missions, but the sovereign nation did not grant permission to enter their airspace and has the capability of shooting down the vehicle (Office of the Secretary of Defense A2). Satellites were thought to be the solution to aerial reconnaissance needs for the United States, because they are a cheap alternative to spy planes like the SR-71 Blackbird. However, satellites have severe limitations such as the enemy knowing when they are overhead and the time it takes to reposition. Manned aircraft flying surveillance missions exposes a flight crew to danger. Unmanned vehicles are best utilized for ISR missions. Unmanned aircraft eliminates the risk to air crew and has the ability stay over a target for long periods of time while being undetected.

2. Strike/Suppression of Enemy Air Defense (SEAD)/ Destruction of Enemy Air Defense (DEAD)

One of the most dangerous missions expected of aircrews is neutralizing an enemy's air defense. To accomplish this mission, manned aircraft are placed in harms way. If the manned aircraft fails its mission there is a possibility of the aircraft being shot down. Even if the aircraft is successful in neutralizing its target, the aircraft might still be at risk from any remaining air defense. Instead, a UAV might jam an air defense system to allow a manned aircraft to destroy it. In the future UAVs will likely be able to jam and neutralize air defense system without the need for manned aircraft.

3. Electronic Attack (EA)

The goal of EA is to use "electromagnetic energy to prevent or reduce an enemy's effective use of the electromagnetic spectrum" (Office of the Secretary of Defense A4).

This mission area prevents the enemy from using their communications network to coordinate their response to an attack. EA can also be used against enemy radar units which will prevent the enemy from seeing an attack coming. A UAV is well suited for this mission because it is hard to detect. A manned aircraft performing this mission is vulnerable to attack until the enemy's defense system is down. This mission area is closely related to SEAD and DEAD.

4. Network Node/Communications Relay

One of the most important support missions that an unmanned vehicle can perform is providing communications to a certain area. A high-altitude flying UAV can help provide a communications network for troops on the ground. UAVs can be easily flown over an operational area rather than communications towers having to be setup to establish a communications network. This allows ground units operating remotely to be able to communicate with command and control (C2). Being able to communicate and coordinate maneuvers is important in the modern era of warfare.

5. Aerial Delivery/Resupply

UAVs biggest asset to this mission area is bringing supplies to remote operating forces without compromising their location. This allows the war fighter to carry fewer supplies because of the capability to deliver essential supplies like food, water, and ammunition. This will allow for covert operations farther and longer into enemy territory.

UAVs can also conduct psychological operations through dispensing leaflets. "Dispensing leaflets has traditionally been performed from C-130s, but the altitudes required to ensure aircrew safety tend to scatter the leaflets over a wide area and reduce their effectiveness" (A8). UAVs can drop leaflets precisely where they need to be placed. This will increase leaflets effectiveness on the targeted population.

6. Battle Damage Assessment (BDA)

This mission area is not directly addressed in the UAV master plan. This mission area is closely related to ISR, but is unique enough to stand as it own mission area.

Aircraft can destroy the infrastructure of a country before ground forces have to fight. This strategy was used in the first Gulf War and in Kosovo. It was also used to take out terrorist training camps. The problem with this strategy is ensuring what was bombed is actually destroyed and not just damaged. Thus, battle-damage assessment is critical. Manned aircraft can provide information about how successful an attack was, but manned aircraft cannot get close enough to provide an accurate assessment. However, UAVs can covertly monitor how the enemy reacts to the strike and can monitor any repairs that are being made, often without the enemy knowing. The UAV can provide BDA information regarding whether the target needs to be bombed again while also providing further intelligence on any new defenses protecting the target.

E. USV MASTER PLAN

USVs are some of the newest autonomous vehicles. The official Department of the Navy USV master plan is undergoing final review (Naval Undersea Warfare Center). NPS review of the draft is included here, with the caveat that the information contained in the document may change.

Future USVs will be launched either from ships at sea or from the shore. USVs do not have a mission area dedicated to ISR, but for each mission area to be successful ISR is needed.

1. Mine Warfare

Mine warfare has long been a problem facing the United States Navy. The USS SAMUEL B. ROBERTS (FFG 58) hit a mine in 1988 and the USS PRINCETON (CG-59) struck a mine in 1991. Mines possess a unique challenge for the Navy. Mines are an asymmetric threat because they are cheap and anyone can make them. Mine clearing ships cannot be everywhere. A terrorist organization can mine an area denying a vital area of operation. Instead of waiting for a mine clearing ship to make it across the ocean, USVs carried by surface vessels can be a quick solution to a mined area. USVs can also carry UUVs to help them accomplish mine warfare. The purpose of mine warfare is establishing operating areas, transit routes, and transient lanes (Naval Undersea Warfare

Center). Mine Warfare also protects sea-lines of communications, offshore fleet operating areas, and littoral penetration areas (Naval Undersea Warfare Center).

2. ASW

Enemy submarines remain among the biggest threats facing the United States Navy. Iran has at least two Kilo class submarines from Russia and eight mini-submarines from North Korea ("Iran Navy"). "After the cold war, the Navy neglected anti-submarine warfare, on the assumption that Soviet subs no longer were a menace. But the proliferation of diesel-electric submarines around the world prompted Navy leaders to rethink their priorities" (NDM). Diesel subs pose an asymmetric threat to the United States Navy because they are cheap and are quiet while running off of batteries. USVs are fast and can cover larger areas in order to protect an operation area from an enemy sub. An advantage that USVs have over traditional platforms for hunting diesel submarines is that USVs can operate in shallow waters that diesel subs operate in and USVs can be a force multiplier by putting multiple moving sensors in the water.

UUVs are well suited for the hold at risk component of ASW. USVs are similarly well suited for Maritime Shield and Protected Passage (Naval Undersea Warfare Center). Maritime shield requires establishing and protecting Carrier or Expeditionary Strike Group (ESG) operating area free of threat submarines (Naval Undersea Warfare Center). Protected passage requires safe passage from one operating area to another free of threat submarines (Naval Undersea Warfare Center). USVs have to patrol, detect, track, hand off, and engage enemy submarines (Naval Undersea Warfare Center).

3. Maritime Security

Vulnerable areas to attack are ports that Navy ships anchor in, both at home and aboard. USVs are essential to stop a future terrorist attack because of their speed and visibility. This mission area has three objectives which area to collect intelligence above and below the surface, deter attacks on ships in ports, while reducing the risk to manned patrol craft (USV). These objectives can be achieved through "persistent littoral ISR, harbor or port monitoring, chemical, biological, nuclear, radiological, explosives detection and localization, surveillance sensor emplacement, battle damage assessment,

and active target designation. Navy ships are most vulnerable in port and the USS COLE incident shows what can happen without adequate port security.

4. Surface Warfare (SUW)

The purpose of USVs performing SUW missions is to reduce the risk to manned platforms by engaging targets with lethal and/or non-lethal weapons (USV). This mission area is not a standalone mission area. Rather, it is like maritime support or SOF support, where the USVs are armed to aid other Navy assets in those mission areas. This concept needs to be incorporated as an overarching theme in the applicable mission areas.

5. Special Operations Forces (SOF) Support

Special operation forces often achieve mission success through stealth and surprise. USVs can aid SOF by helping collect information before an operation takes place. For instance, USVs can go ahead of the SOF on riverine operations to investigate possible ambush positions. This mission is called around-the-bend ISR (Naval Undersea Warfare Center). USVs can perform payload delivery missions to deliver supplies to SOFs operating in remote areas, which means SOFs can carry fewer supplies. The supplies delivery can be covertly delivered preserving the location of the SOF rather than a manned platform delivery giving away their location. Since USVs are the newest type of unmanned vehicle, their full potential in this area is not yet fully known.

6. Electronic Warfare (EW) and Information Operations

USVs can be an asset in supporting fleet operations by performing EW. USVs speed, range, and power supply makes them ideal for EW because manned platforms do not need to perform these types of dangerous missions. A ship's biggest threat comes from anti-ship missiles, and as ships like the LCS operate closer to the shore, the threat becomes greater. USVs can act like a missile sponge to protect assets by sending out signals to attract incoming missiles. USVs can also perform communication jamming, Global Position System (GPS) jamming, maritime improvised explosive device (MIED) clearing, and can even act as an acoustic decoy for ships by generating false ship sounds (Naval Undersea Warfare Center)

7. Maritime Interdiction Operations (MIO)

USV role in MIO is to support manned platforms in order to make MIO safer and more effective. A MIO are activities to divert, disrupt, delay, or destroy the enemy's military potential before it can be utilized (Naval Undersea Warfare Center). USVs can help manned platforms perform MIO by deriving the intent of a vessel, which can possibly draw fire (Naval Undersea Warfare Center). For example, USVs can monitor the opposite side of a vessel being investigated to ensure that the vessel does not try to jettison cargo or have people trying to escape before an inspection by the manned platforms (Naval Undersea Warfare Center). USVs sensors are also helpful in detecting if a vessel has an unusual feature like hidden compartments or a radiological signature (Naval Undersea Warfare Center). USVs are not expected to perform MIO in isolation, but rather are a force multiplier aiding manned platforms.

8. Other Mission Areas not Covered by the USV Master Plan

a. Small Boat Threat

Since the USS COLE incident, the threat of small boat attack has been great. Small boats are able to deliver enough firepower that can neutralize any Navy ship. A Navy ship can defend itself very effectively through its self defense measures. However, it only takes one small boat to get through to neutralize a Navy warship. A swarm of small boats can overwhelm a Navy ship's defense and allow at least one small boat to get through. USVs may be helpful in neutralizing this threat. USVs can investigate suspicious vehicles at greater range to help isolate who can be a threat without putting sailors in harms way and perhaps even neutralize even take out small boats that try to attack a Navy vessel.

b. Oceanography

USVs can operate longer and faster than UUVs. USVs can provide a quicker survey of a larger area of ocean than UUVs. However, if an area needs to be surveyed in detail, teams of USVs and UUVs can accomplish that mission. Currently, manned surface vessels have to perform the mission of oceanography. Oceanography missions are dull and long, and are better suited for unmanned vehicles. This mission

area is an example of a force multiplier because less manned platforms can provide more functionality through the employment of unmanned vehicles.

F. UGV MASTER PLAN

Since there is not an official document published as the UGV master plan for the Navy, this thesis uses the *Joint Robotics Program Master Plan* which is published by OUSD Defense Systems/Land Warfare and Munitions. This document is intended to be "an executable Master plan/ roadmap that moves toward becoming the single DoD position for the domain of Unmanned systems" (Department of Defense Joint Robotics Program 2-12). However, it currently only covers UGVs. There are numerous types of UGVs listed, each performing different missions. One issue that arises from that diversity is trying to provide a common control unit so that war fighters can concentrate on performing critical missions in fighting the war.

The master plan identifies following missions for ground vehicles in the future.

- Detection, neutralization, and breaching of minefields and other obstacles
- Reconnaissance, Surveillance, and Target Acquisition (RSTA) of unexploded ordnance (UXO)
- UXO clearance
- Contaminated area operations/denied areas
- Force protection
- Physical security
- Logistics
- Firefighting
- Urban warfare
- Weapons employment
- Search and Rescue

Due to limitations of the current AUVW and few ground vehicles to experiment with at NPS, support for UGVs is left as future work.

G. MISSION AREA REQUIREMENTS

This table shows what mission areas future unmanned vehicles are expected to perform. This table only includes UAVs, USVs, and UUVs. The following table shows that certain mission areas overlap all types of vehicles. These missions are the most critical for the AUV Workbench to support.

Mission	UUV	UAV	USV
Intelligence Surveillance Reconnaissance	X	X	X
Mine Warfare	X		X
Anti-Submarine Warfare	X		X
Inspection and Identification	X		
Oceanography	X		X
Communications	X	X	
Payload Delivery	X	X	X
Information Operations	X		X
Strike	X	X	
Suppression of Enemy Air Defense and Destruction of Enemy Air Defense		X	
Electronic Attack		X	X

Table 4. Missions areas that unmanned vehicles are expected to perform

H. SUMMARY

This chapter outlines the missions that robots of the future are expected to complete. The first master plan that was reviewed was the mission areas for UUVs which are ISR, MCM, ASW, Inspection and ID, Oceanography, Communications and Navigation Network Node, Payload Delivery, Information Operations, and Time Critical Strike. The second master plan that was reviewed was the UAV's and their future mission areas defined by the master plan are ISR; Strike, SEAD and DEAD, EA, Network Node and Communications Relay, and Aerial Delivery and resupply. The USV master plan is still pending publication but the initial mission areas are: Mine Warfare,

ASW, Maritime Security, Surface Warfare, Special Operation Forces Support, EW and IO, and Maritime Interdiction Operations. The final section of this chapter took all the mission areas defined by the master plans and synthesized them into common mission areas to see what missions areas are expected from each class of unmanned vehicle. Excellent conceptual consistency and coherence was found when comparing the master plans.

V. AUTONOMOUS UNMANNED VEHICLE WORKBENCH (AUVW)

A. INTRODUCTION

The AUVW has been an ongoing project at NPS that has been pursued for the last fifteen years. Its mission is to provide a common interface for planning, rehearsal, real-time execution, and replay for autonomous vehicles. This chapter provides an overview of the AUVW by reviewing the technologies utilized by the AUVW, Autonomous Vehicle Command Language (AVCL), and the features of the AUVW.

B. AUTONOMOUS VEHICLE COMMAND LANGUAGE (AVCL)

The motivation for AVCL was to bridge the gap of interoperability between robots in order to control multiple robots (Davis). One way to solve the problem of interoperability is to have a standard set of orders that all military robots have to understand; however, that has not been previously done. AVCL needs to be mapped to a robot's command language. Once that is completed, AVCL can be translated from the robot's language to AVCL and visa versa. Translators can also be written to change the robot's language into XML-based AVCL. Conversely, an XLST can convert XML used in the workbench to the robot's command language. Figure 26 shows how AVCL was mapped to the ARIES waypoint command.

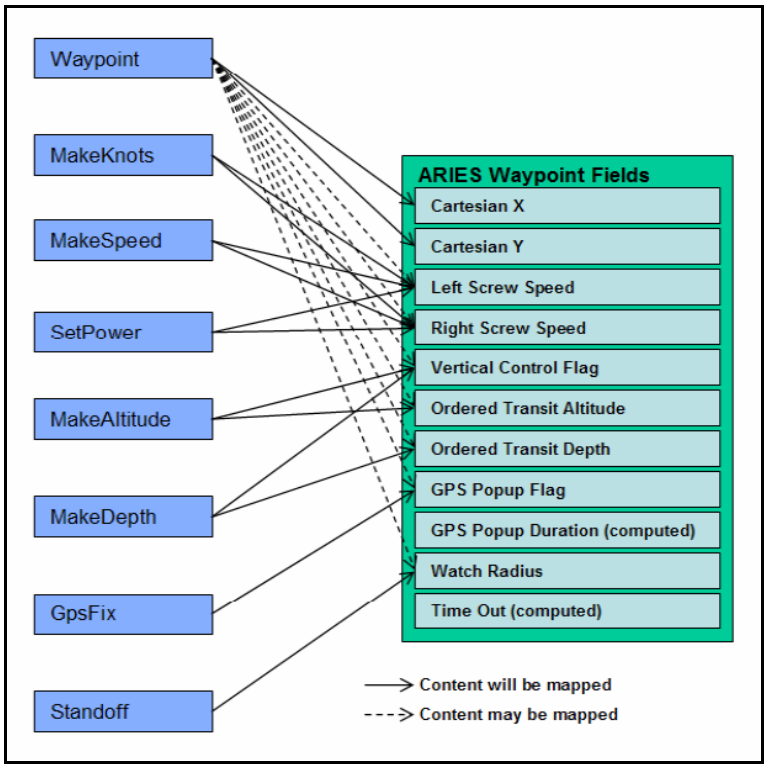

Figure 24. This illustrates AVCL to the ARIES waypoint command translate from (Davis 143)

Conceptually, AVCL is analogous to standardized Officer of the Deck commands for the AUV Workbench to order robots around. AVCL is needed because no two robots are alike, robots are usually built by different people, have different sensors, and have to perform different types of missions. As a result , each robot typically has its own software-based developed command language. AVCL solves that problem because every robot has the same basic commands like go there, wait, change speed, etc.

Different vehicle types can have significantly different commands. For instance, a UAV can do things that a USV cannot such as change altitude. Therefore, some commands are unique to a vehicle type. Even though a robot of a certain type might be given a command, that does not mean it can perform that task. The robot must also have the physical ability to perform that command; for example, if a UUV robot does not have side thrusters, it cannot perform the MoveLateral command. The AVCL schema can be updated so each robot has its own set of commands. Right now, the schema is only broken down into UAV, USV, UGV, and UUV commands.

1. Agenda Commands

Agenda missions are different from imperative scripted "do this, do that" missions because the user does not have to give the robot every command. Instead, agenda missions allow the robot to make decisions based on different algorithms. A wide variety of commands has been defined. The AUVW does not support all the agenda commands. As of this writing, the only agenda command that is supported is the search command.

When an agenda mission is run in the AUVW, the workbench will output a scripted mission so the user can review the mission and then modify the mission. Table 5 lists the agenda missions commands available through the AVCL schema.

Commands	Description
Attack	The vehicle will engage targets within the operating area
Decontaminate	The vehicle will remove contaminants from the operating area
Demolish	The vehicle will physically destroy a target within the operating area
IlluminateArea	The vehicle will illuminate the operation area
Jam	The vehicle will jam any use of radar or communications within the operation area
MarkTarget	The vehicle will mark targets within the operation area
MonitorTransmissions	The vehicle will monitor electronic transmissions in a certain frequency range within the operation area
Patrol	The vehicle will patrol the operation area
Rendezvous	The vehicle will meet another vehicle in the operation area
Reposition	The vehicle will move to a different location
SampleEnvironment	The vehicle will sample the environments for contaminant within the operation area
Search	The vehicle will search the operation area with its sensors

Table 5. AVCL agenda commands. Agenda commands gives a robot a task to complete and the robot figures out how to complete the mission.

2. Script Commands

Script commands make the user give the vehicle all the commands needed to accomplish its mission. These commands are straight foreword and the robot is told exactly what to do. Some commands are common to all vehicles and those commands are listed in the Table 6.

Table 7 presents the script commands unique to UUVs, Table 8 presents the script commands unique to UAVs, and Table 9 presents script commands unique to USVs.

Command	Description
CompositeWaypoint	Orders the vehicle to pattern of multiple waypoints.
FollowBeacon	Orders the vehicle to follow the source of a beacon or transponder.
Help	Causes a list of valid commands to be printed to the console (if available).
Loiter	Maintain position in the vicinity of a specified point for a specified period of time (hover not required).
MakeHeading	Set commanded vehicle heading (disables waypoint or recovery control).
MakeKnots	Set the commanded forward speed in knots.
MakeSpeed	Set the commanded forward speed in meters per second.
MetaCommand	Command with no action required, but containing information relevant to the mission or vehicle
MissionScript	Loads a new mission script from a specified file and continues execution with the new script
MissionScriptInline	Loads a new mission script from a specified file and inlines the new script into the existing script.
Quit	End the vehicle mission after zeroing all control settings (does not initiate surfacing procedure prior to shutdown).
Realtime	Causes execution to run in realtime (or turns realtime execution off).
SendMessage	Send a specified message to one or more vehicles using the designated communications method.
SetPosition	Update of unmanned underwater vehicle position in the world (new navigation fix has been obtained).
SetStandoff	Resets the acceptable standoff radius around hoverpoints and waypoints.
SetTime	Resets the vehicle's mission time to a specified value
SetTimeStep	Reset the elapsed time for each closed loop control cycle
Trace	Turns the vehicle trace feature (runtime debug messages printed to console) on or off.
Wait	Causes the vehicle to wait for a specified time duration before proceeding to the next command.
WaitUntilTime	Causes the vehicle to wait until a specified time before proceeding to the next command.
Waypoint	Command the vehicle to transit to a specified location. Vehicle will not necessarily stop when position is reached (vehicle specific).

Table 6. AVCL script commands common to all vehicle types. Script missions are individual commands that the robot will perform. The user has to give multiple script commands for a robot to complete a mission.

Command	Description
GpsFix	Orders the vehicle to surface for a gps fix or resume mission after obtaining a gps fix.
Hover	Command the vehicle to transit to (if required) and maintain position at a specified position.
MakeAltitude	Set commanded vehicle altitude above the bottom.
MakeDepth	Set commanded vehicle depth.
MoveLateral	Commands the vehicle to slide laterally with a fixed thruster setting as a percentage of max speed (turns off all automatic control modes).
MoveRotate	Commands the vehicle to rotate (yaw) with a fixed thruster setting as a percentage of max speed (turns off all automatic control modes).
Recover	Commands the vehicle to recover at a recovering station (vehicle should be directly in front of station, but heading can be off).
SetPlanes	Manually set bow and/or stern plane deflection angle as a percent of max authority (turns off all automatic control modes).
SetPower	Manually set one or more propeller speeds as a percentage of max speed
SetRudder	Manually set rudder deflection as a percentage of max speed (turns off all automatic control modes).
SetSonar	Set the specied steerable sonar to automatic scan or a manually commanded bearing and elevation.
SetThruster	Manually set bow and/or stern plane deflection angle as a percentage of max power (turns off all automatic control modes).
TakeStation	Commands the vehicle to take up a specified fixed station relative to an external object
Thrusters	Enable or disable the vehicle's body (lateral and vertical) thrusters (may be overridden by some vehicle commands).

Table 7. AVCL script commands unique to UUVs. UUVS have some unique commands available to them because of the environment they operate in.

Command	Description
MakeAltitudeAGL	Set commanded vehicle altitude in mean sea level.
MakeAltitudeMSL	Set commanded vehicle altitude in mean sea level.
MakeClimbRate	Set commanded vehicle climb rate as a percentage of maximum
MakeTurnRate	Set commanded vehicle turn rate as a percentage of maximum
SetAileron	Manually set aeleron deflection as a percentage of max authority (positive will result in right roll, turns off all automatic control modes).
SetElevator	Manually set elevator as a percentage of max authority (port and starboard) deflection (turns off all automatic control modes).
SetPower	Manually set the commanded engine power as a percentage of max power.
SetRudder	Manually set rudder deflection as a percent of max deflection (turns off all automatic control modes).

Table 8. AVCL script commands unique to UAVs. UAVS have some unique commands available to them because of the environment they operate in.

Command	Description
SetPower	Manually set one or more propeller speeds as a percentage of max speed.
SetRudder	Manually set rudder deflection as a percentage of max deflection (turns off all automatic control modes).

Table 9. AVCL script commands unique to USVs. UUVS have some unique commands available to them because of the environment they operate in.

C. CURRENT CAPABILITIES OF AUVW

1. Visual Interface

a. Open Map

Open Map is an open source software tool that allows different geospatial information system (GIS) data sets to be displayed into the AUVW. As with most GIS displays, data sets are layered in Open Map. The Figure 25 shows planned AUV routes above the set of GIS data, namely a topographic map of Monterey Bay area with contour lines. This application allows the user to plan a mission using geographic landmarks to see where the robot will actually operate instead of having to enter latitude and longitude

coordinates. This feature increases the situational awareness of the user, and probability of mission success for the robot because the user can easily see the path of the robot will take over the features and terrain.

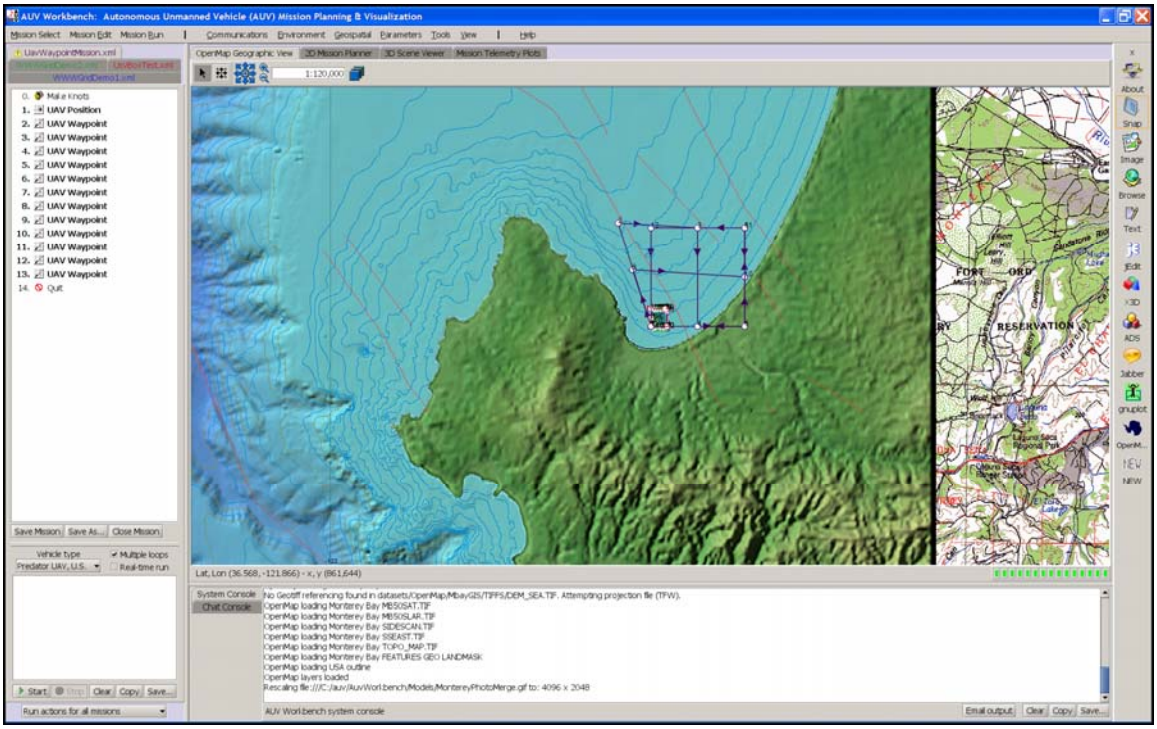

Figure 25. Open Map screen shot from the AUVW. The Open Map feature allows layering of different GIS data sets on top of each other

b. 2D Mission Planner

The 2D interface is a quick and easy way to edit and create missions. The 2D mission planner is on a Cartesian grid system. A mission can be edited through clicking and dragging waypoint, double clicking on a waypoint to edit it through a graphical user interface, or editing the XML directly. A magnetic rose can be placed on top of the 2D mission planner to aid in the mission planning.

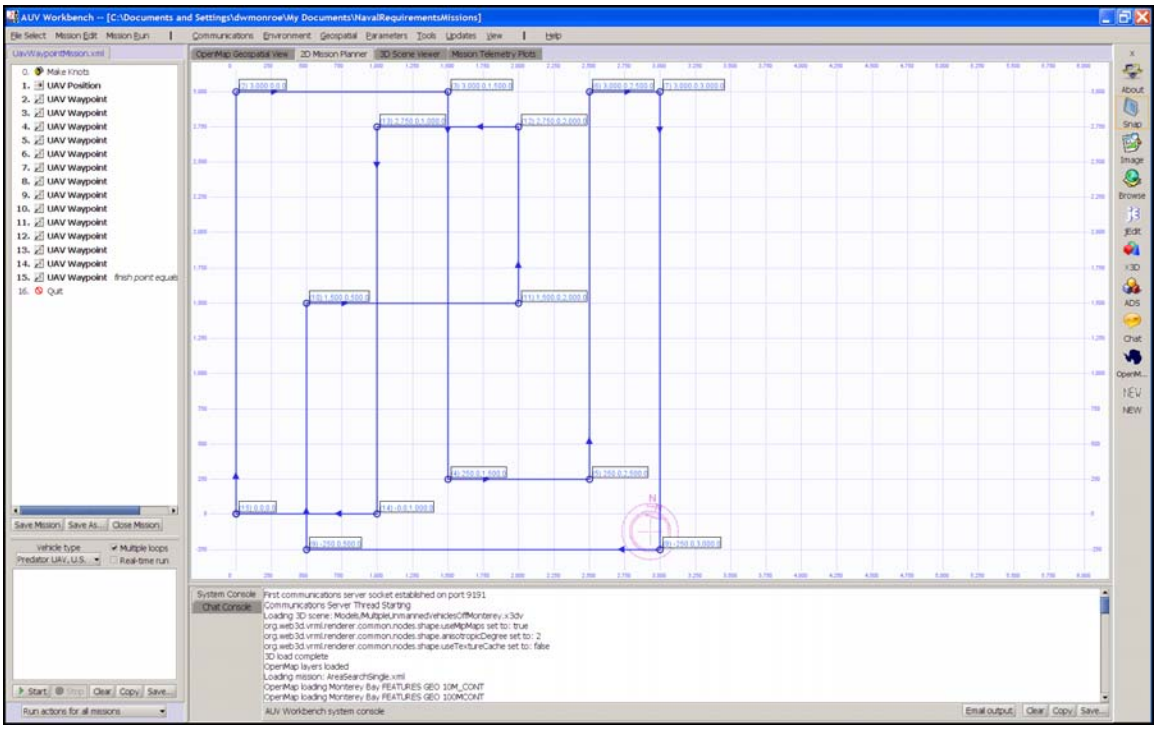

Figure 26. The 2D Mission Planner in the AUVW.

c. X3D Scene Viewer

The X3D scene viewer allows the user to visualize the robot operating in a 3D environment. The vehicles are made using X3D and are archived into the SAVAGE archive online. The archive is located at https://savage.nps.edu/Savage. There are several different robot models in the archive that can be used in the workbench. The Savage Defense archive contains different 3D scenes. The Savage Defense archive is For Official Use Only (FOUO) and restricted to unclassified models.

The X3D scene allows users to see the terrain and bathymetry that the robot is operating above, visualizing how the robot reacts to ordered commands. In the X3D scene waypoints are laid out so the user can see how well the robot stayed on track. The user can even see how the robot's control surfaces change to perform a command, permitting detailed trouble shooting of robot behavior while analyzing high-fidelity physics-based simulation results.

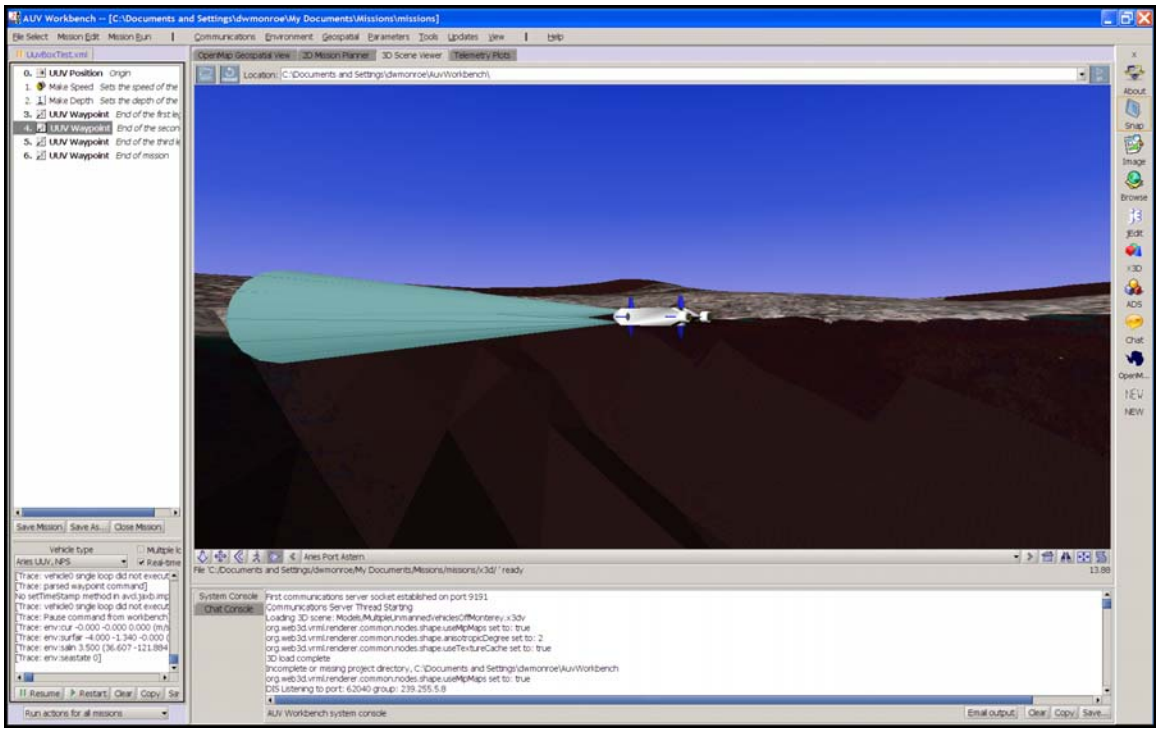

Figure 27. The X3D Scene Viewer in the AUVW

d. Telemetry Plots

The newest visual aspect of the workbench is the telemetry plots of mission that was rehearsed in the workbench or of an actual robot mission being played back in the workbench. Telemetry plots capture the state vector of a robot through the mission and are plotted over time. The plots available are Geographic XY plot, Position X Y Z, Orientations phi theta psi, and rotational velocities p q r. Figure 28 shows the different graphs available. Detailed plots of telemetry state vectors are often essentially for mission reconstruction and precise tuning of control-systems response.

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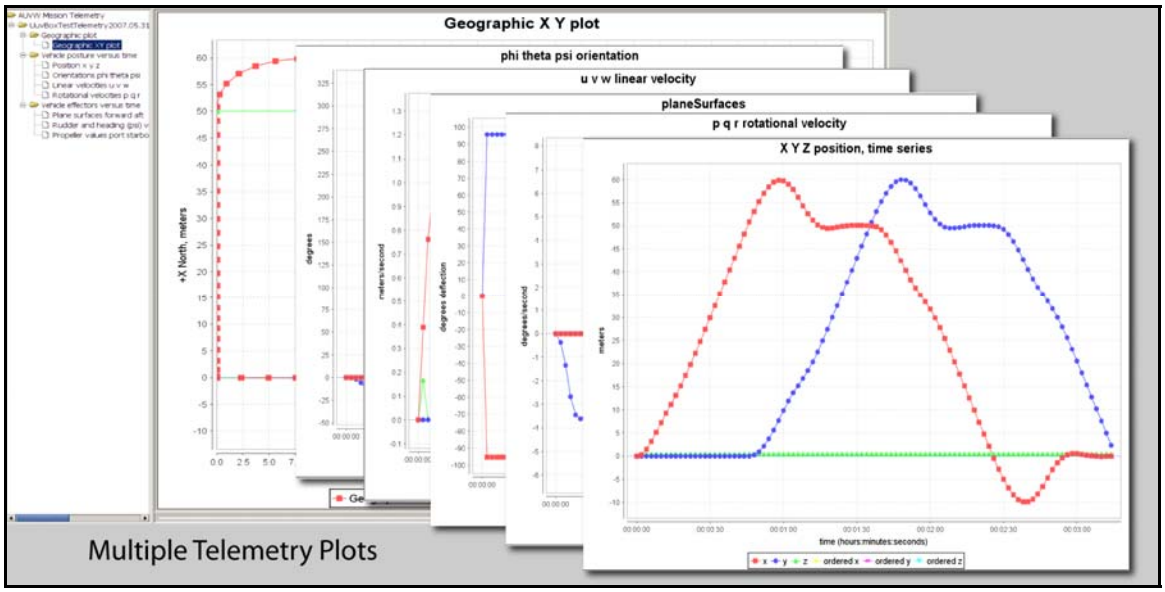
Geographic X Y plot
phi theta psi orientation
u v w linear velocity
planeSurfaces
p q r rotational velocity
X Y Z position, time series
Multiple Telemetry Plots

Figure 28. Different types of graphs are available to show the various robot telemetry parameters collected during simulated or actual missions.

2. Mission Planning

a. Scripted Missions

Scripted missions are straight-forward to create. Before an actual mission, the user plans exactly what the robot is going to do. This includes where to go, which way to move, and how fast the robot will to proceed. The robot then uses AVCL script commands perform the mission. After the user is satisfied with mission performance in the workbench, it can be exported from AVCL to the actual robot command language for subsequent performance in the real world. Figure 29 shows how the mission tracks appear in the 2D mission planner. Figure 30 shows the corresponding command summary for the mission.

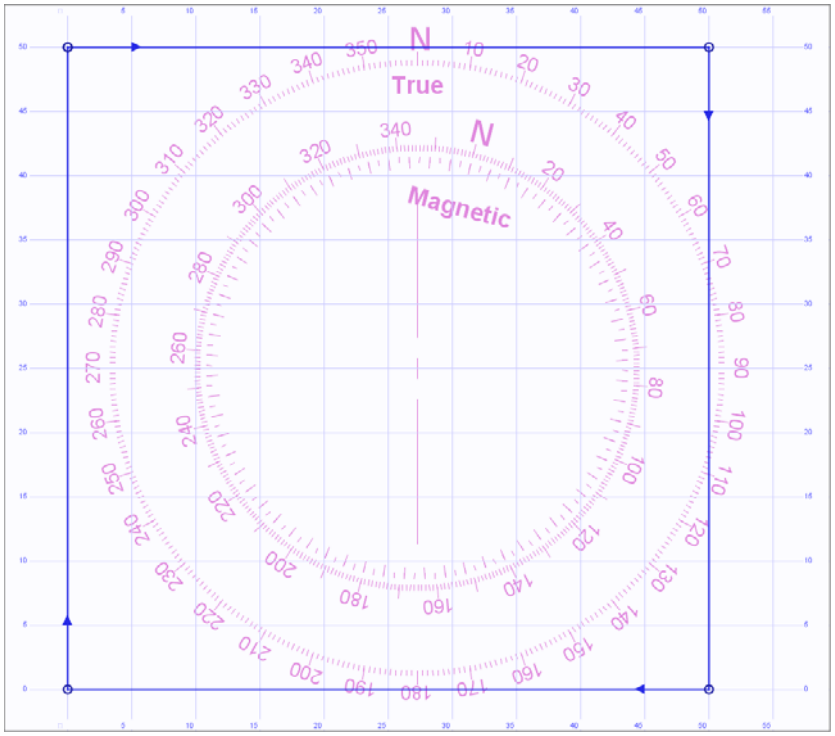

Figure 29. A screen shot of a scripted mission from the AUVW 2D mission planner with a compass rose

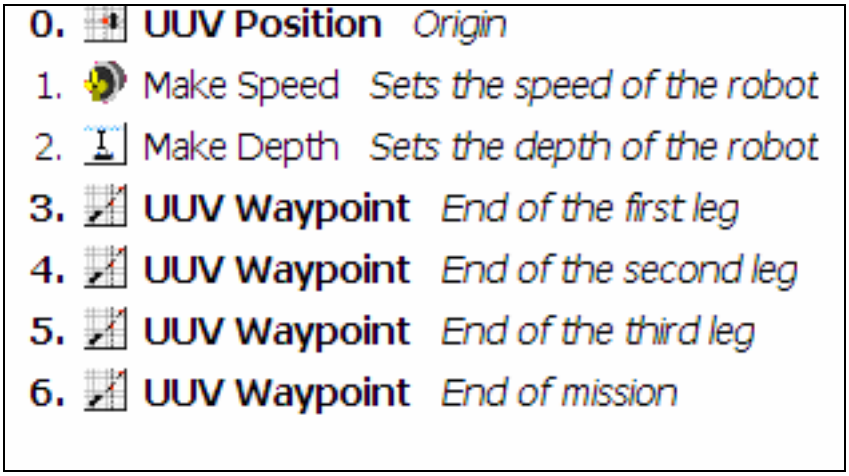
0. UUV Position Origin
1. Make Speed Sets the speed of the robot
2. Make Depth Sets the depth of the robot
3. UUV Waypoint End of the first leg
4. UUV Waypoint End of the second leg
5. UUV Waypoint End of the third leg
6. UUV Waypoint End of mission

Figure 30. The commands for the box script mission shown in figure 31.

b. Agenda Missions

Agenda missions provide the flexibility needed for more complex mission tasks. Sometimes it is not practical to plan the individual waypoints of a mission. Some tasks "require activities that cannot be commanded using the existing task-level behavior

set (e.g., there is no task-level behavior available to command the vehicle to decontaminate area)" (Davis, 159). Also, scripted missions assume that each step of the mission is executed and completed successful. Agenda missions were develop to overcome these problems of scripted missions.

Agenda missions allow the robot to respond intelligently to changing circumstances. The mission programmer can say that if the robot succeeds on one task, then do this next task but if a task fails to complete a given task. Then it will undertake a different response task.

AVCL implements search patterns described by the International Aeronautical and Maritime Search and Rescue Manual. Differently shaped search areas result in different search patterns. The agenda AUVW planner can also support avoid areas which the robot will not enter but instead will find the best route around. Figure 31 shows an example agenda mission demonstrating these features.

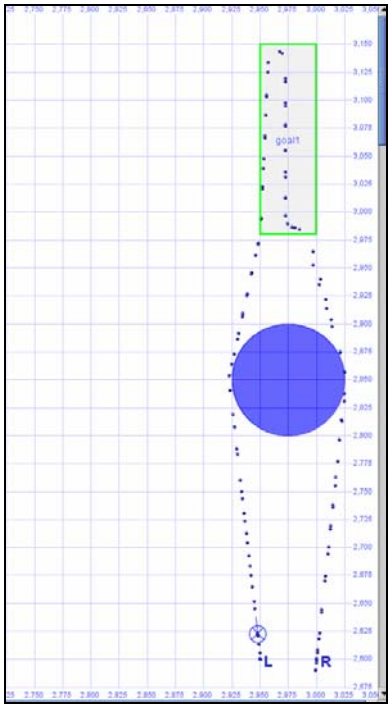

Figure 31. Agenda Mission where the vehicle has to avoid the circle, obstacle area, search the rectangle area and return. The dotted-line track indicates successful completion from launch to recovery point.

3. Mission Telemetry Playback

The workbench has the ability to playback telemetry data recording from previous missions. These missions include missions rehearsed in the workbench or missions that actual robots preformed. The AUVW can playback Scan Eagle, Rascal, Sea Fox, Solar UUV, and Remus missions. A translation is performed, first importing each native telemetry format into XML-based AVCL form. The translation import process reads a flat file such as a comma-delimited file by mapping appropriate entries into AVCL.

This allows the mission results to be played back, creating a variety of plots and visualizations. Since robot telemetry formats can change over time, archiving both forms is an excellent way to ensure long-term readability and analyzability of recorder results.

4. Weather constraints

The AUV Workbench as an excellent rehearsal tool for unmanned vehicles. Unmanned Underwater Vehicles biggest limitation is its power supply. The weather can have a drastic impact on the power consumption of an unmanned vehicle. For example, if the vehicle has to fight against currents the vehicle must use more energy to stay on course. Evaluating the predicted consumption is useful when planning a mission. The AUV Workbench allows the user to manually enter data into the simulation as shown in the Figure 32.

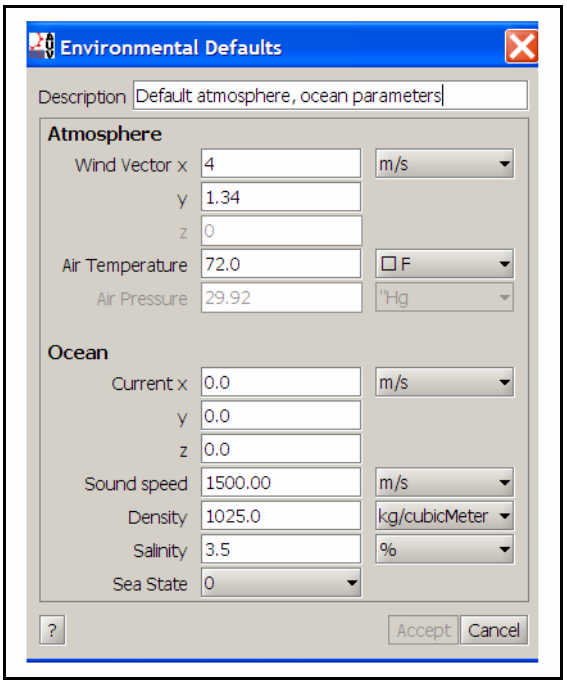

Figure 32. This graphical user interface allows the user to enter a variety of values for the environmental parameters.

Allowing the user to set certain weather parameters is helpful. However, the weather is always changing and cannot be captured by static values. The AUV Workbench also has the capability to get data from different weather forecasting sources that are available via the internet. The user can use this data to rehearse missions using data from future operation areas. The following figure is the graphical user interface that allows users to select data sources for each environmental parameter.

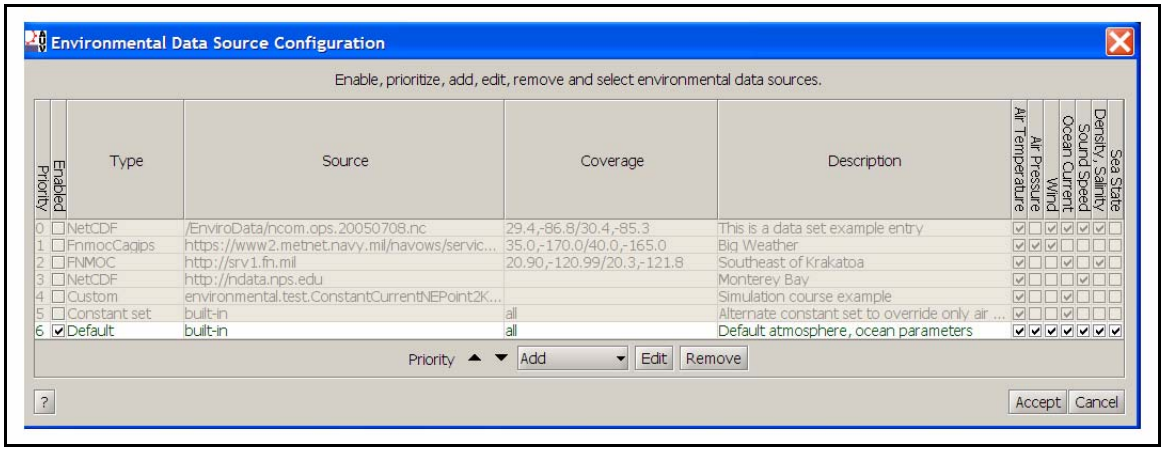

Figure 33. The AUVW's environmental data source configuration GUI. This allows user to edit and add data sources to use for a simulation.

5. Adding Vehicles to AUVW

AUVW allows any future vehicle to be added to it. An X3D model is first needed to provide a visual representation. Dynamics and control coefficients for the vehicle also need to be set. The coefficients can be obtained either from the manufacture or from sea trials. Special classes can be written and added to the open-source code base if the control equations or dynamics are significantly different from the already parameterized models present in The Workbench. This approach allows the workbench to be scalable for the future.

D. SUMMARY

This chapter introduced the open source technologies utilized by The AUV Workbench. AVCL allows The Workbench to be extended to any robot command language. Then the capabilities of the workbench were explained.

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VI. AUTONOMOUS VEHICLE EXEMPLAR MISSIONS

A. INTRODUCTION

The master plans examined in Chapter IV defined the types of missions that need to be performed by autonomous vehicles. In order for the AUVW to be an effective tool, it must support those missions. This chapter looks at each mission requirement and plans ISR, Mine Warfare, ASW, Inspection/ID, Oceanography, Communications, Payload Delivery, Jamming, and Strike missions using the AUVW. The AUVW is then graded on how well it supports each type of mission.

B. INTELLIGENCE, SURVEILLANCE RECONNAISSANCE (ISR)

1. Summary of Mission Requirements

Every vehicle type is expected to perform ISR missions. ISR is one of the most critical missions that unmanned vehicles have to perform because up to date intelligence is needed whenever planning or conducting military operations.

2. Workbench Strengths

The Open Map feature allows the user to easily plan an ISR mission because the user can plan the mission over a map of the targeted area. This functionality allows the user to see where the robot will be operating rather than entering coordinates.

3. Workbench Weaknesses

A weakness of planning an ISR mission in The AUV Workbench is that there is not an agenda mission option to plan it. Such an option might allow the user to define the area where an ISR mission is expected to be conducted. Another issue when planning this type of mission is that there is no way to control a robot's sensors. There needs to be an AVCL script command to control sensors. Currently to command a robot's sensors the metaCommand was used.

4. Example Mission

The exemplar mission for ISR requires a vehicle to patrol off a coast so that it can collect sensor information. The UUV then moves close to the shore and performs multiple loops collecting data for future missions.

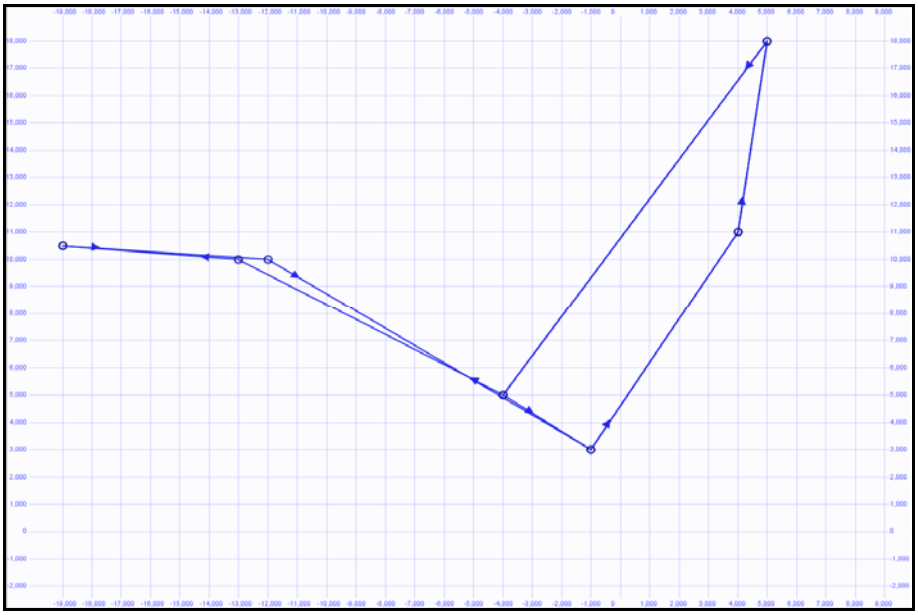

Figure 34. Intelligence Surveillance Reconnaissance mission planned in the 2D mission planner, shown in a solitary 2D display.

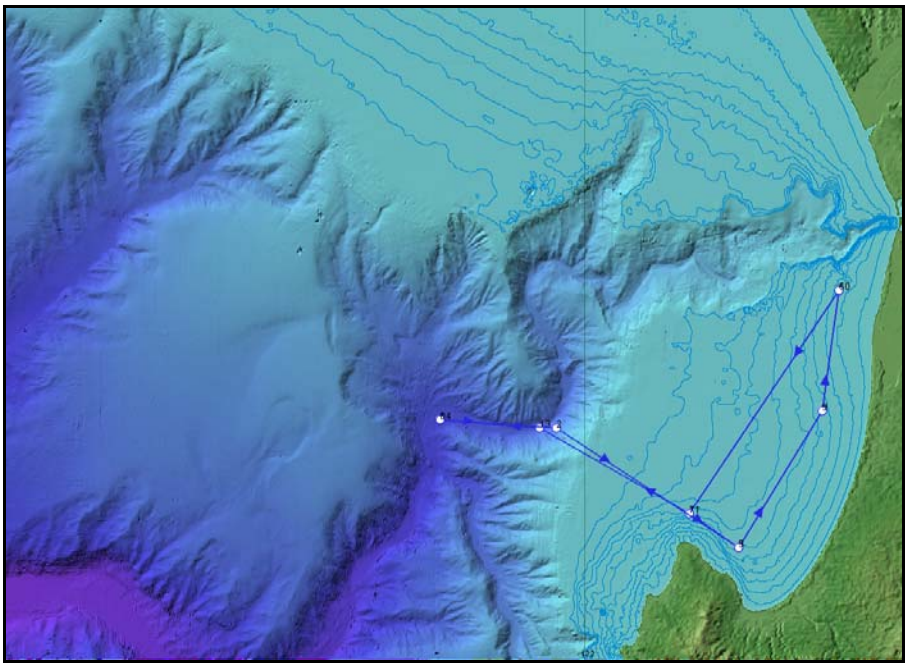

Figure 35. Intelligence Surveillance Reconnaissance mission in the Open Map view, showing proximity to the surveyed area and the use of the deep channel for covert launch and recovery.

0. **UUV Position** *Sets the inital position of the robot*
1. Make Speed *Sets the inital speed for the robot*
2. **UUV Waypoint** *Start approach to mission area*
3. **UUV Waypoint** *The point where the ISR mission begins*
4. Make Depth *The UUV surfaces to collect above the surface data*
5. **UUV Waypoint** *End of the first leg on the first loop*
6. **UUV Waypoint** *End of the second leg of the first loop*
7. **UUV Waypoint** *End of the third leg of the first loop*
8. **UUV Waypoint** *Start of the second loop*
9. **UUV Waypoint** *End of the second loop first loop*
10. **UUV Waypoint** *End of the second loop's second leg*
11. **UUV Waypoint** *End of the ISR mission*
12. Make Depth *The robot dives to covertly go back to its recovery position*
13. **UUV Waypoint** *Vehicle moves towards recovery position*
14. **UUV Waypoint** *The recovery position*
15. Quit

Figure 36. The AVCL commands for the Intelligence Surveillance Reconnaissance mission

C. MINE WARFARE (MIW)

1. Summary of Mission Requirements

Mine warfare is a dangerous mission that robots need to perform in order to keep manned platforms out of harms way.

2. Workbench Strengths

The search agenda mission can allow the user to create a large and complex search area quickly. This saves the user from having to script every waypoint necessary to complete this mission. Agenda missions export the mission into a script mission after it is run in the workbench. This can allow the user to fix any logic errors in the search pattern

3. Workbench Weaknesses

The main problem with this mission area in the AUVW is it can only search an area. If the vehicle finds a mine, it has to identify it and then neutralize it. The AUVW needs allow robots to be programmed to be able response if they find a mine. For example, the response can include communicating to the mother ship. The AUVW needs the ability to allow the user tell which parameter, like coverage area or speed, is most important. The workbench can then develop the best search pattern for the users needs.

4. Example Mission

For this mission an UUV will search one area for mines, then if it does not find any mines, it will move to the second search area. After completing search area number two, it moves to its recovery location while avoiding an area representing a possible sand bar.

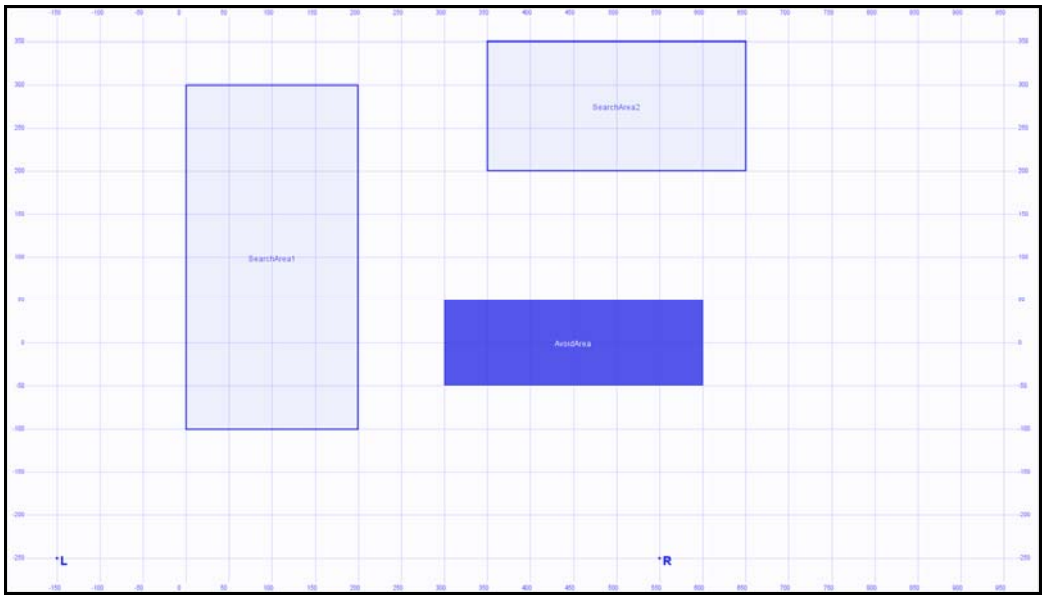

Figure 37. Mine Warfare planned in the 2D mission planner, shown in a solitary 2D display

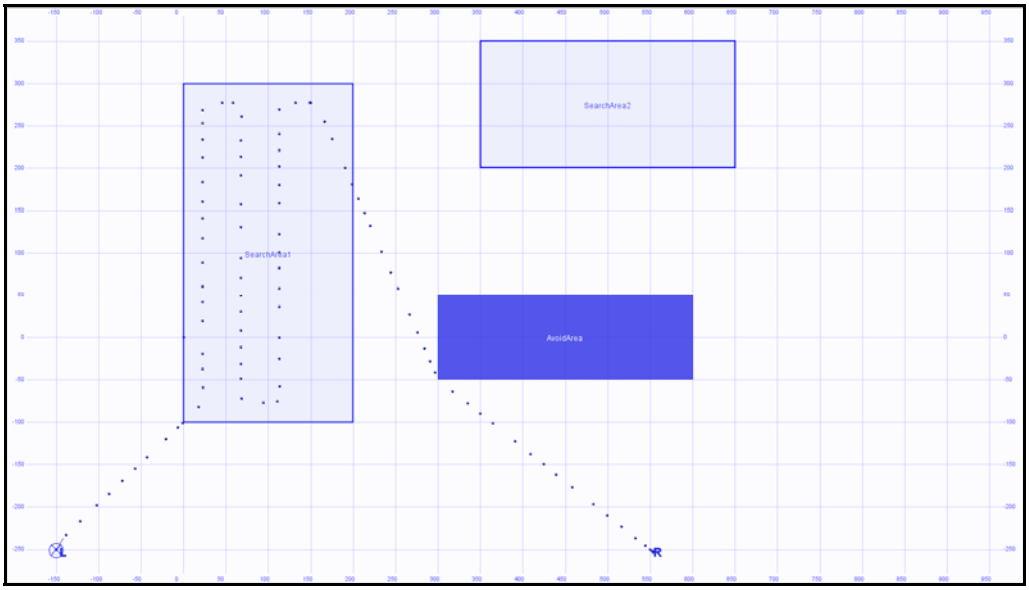

Figure 38. Mine Warfare mission after it is run in the workbench. The dots show the path that the robot took. Successful completion of the search and location of the target in Area 1 eliminated the need to search Area 2

D. ANTI-SUBMARINE WARFARE (ASW)

1. Summary of Mission Requirements

This section only covers the Hold at Risk mission. The UUVs mission is to monitor enemy sub movements in and out of a port. Once the UUV is retrieved by a mother ship, the data of the enemy movements are known. As communications improve in the underwater realm, the UUV could alert US forces real-time when an enemy sub is leaving the port. If robots are trusted, in the future they could engage the enemy sub.

2. Workbench Strengths

The AUVW does an adequate job in planning a hold at risk mission but AVCL currently lacks the ability to tell the robot what to do when it detects a sub. For example, should the robot communicate with the mother ship that an enemy sub is heading out to sea or else launch an offensive torpedo. Further work in AVCL and the workbench is needed to explore thee scenarios.

3. Workbench Weaknesses

The main weakness in this area is that the AUVW cannot tell the robot how to react if it detects an enemy sub. Such a capability likely needs to be added to AVCL agenda-mission representations.

4. Example Mission

This mission is based of the German pocket battleship GRAF SPEE in World War II. The English damaged the GRAF SPEE and forced it to a neutral port in Uruguay. A couple English ships were able to hold the GRAF SPEE in port by cutting of its path to the sea until a superior force could arrive. The GRAF SPEE had to leave the neural port after 72 hours because of the rules of war. This allowed the English to spread propaganda that a superior English force was waiting for the GRAF SPEE. GRAF SPEE was scuttled to prevent any loss of life.

This scenario shows why hold at risk is important; if the GRAF SPEE would have made it, back to Germany could have been repaired so it could of continued hunting merchant ships. In contemporary scenarios, hold at risk missions might be used to keep enemy submarines in port. Additional ASW search missions are examined in (Seguin).

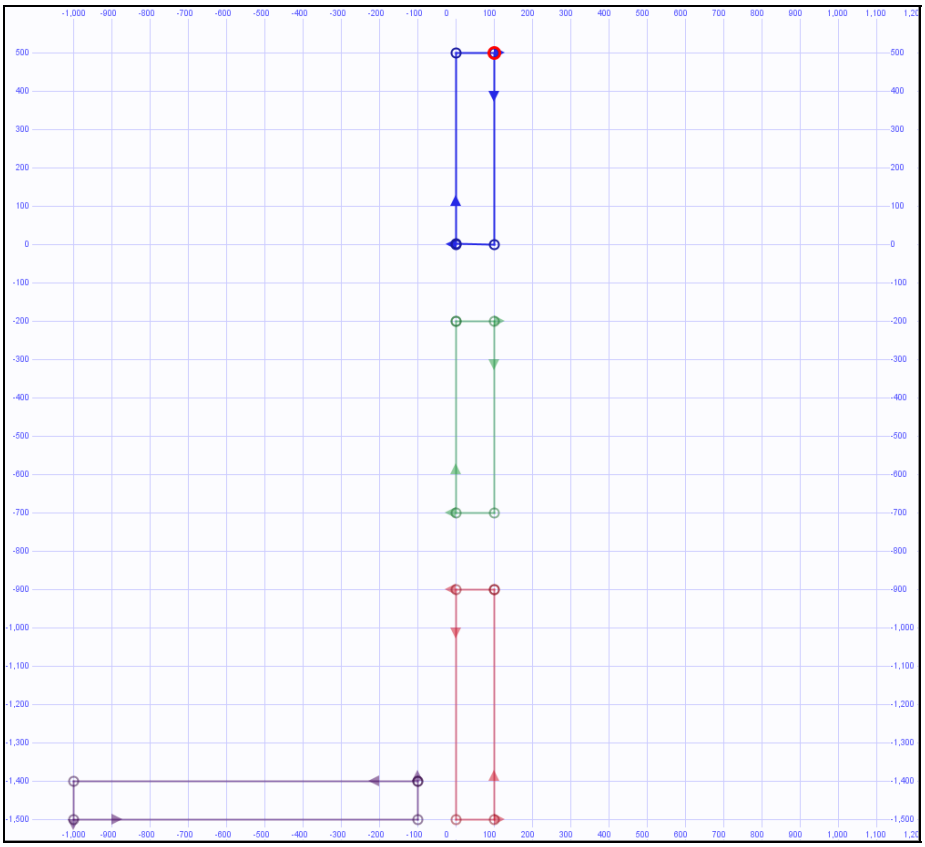

Figure 39. Anti-Submarine Warfare Hold at Risk mission planned in the 2D mission planner, shown in a solitary 2D display

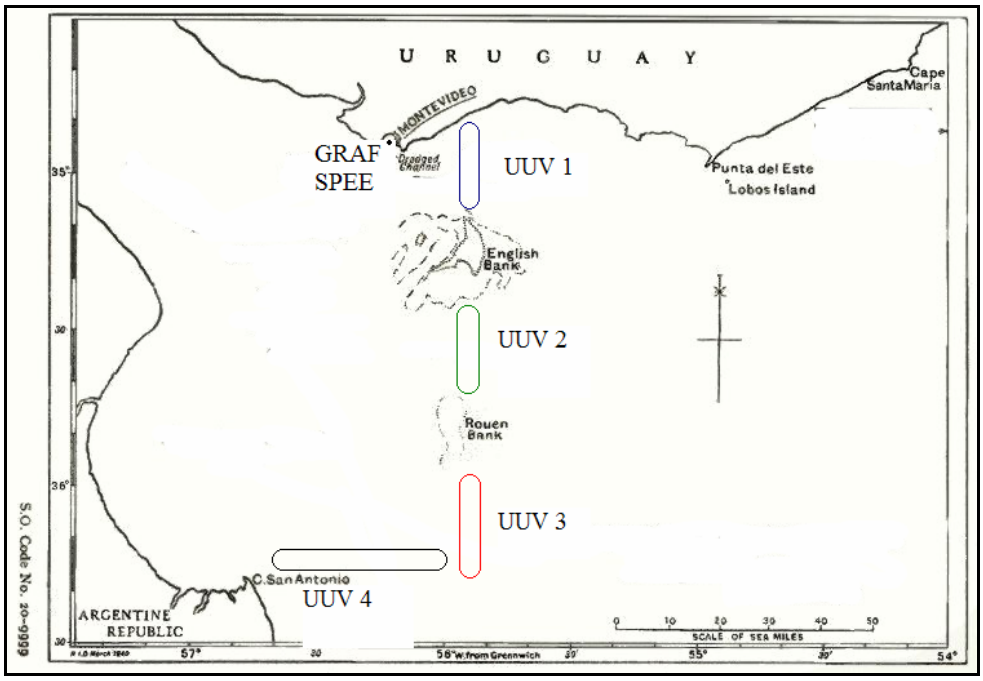

Figure 40. Four UUVs performing a hold at risk mission to keep the Graf Spee in port. (Wikipedia contributors)

E. INSPECTION AND IDENTIFICATION

1. Summary of Mission Requirements

A warship in port is vulnerable to attack from terrorists. Attackers might swim up to ship and place a bomb on its hull. Robots are used to sanitize hulls periodically. The robot can either perform a quick sweep around a hull of ship, or else the robot could sweep under the ship to look for a suspicious object. Performing this mission with robots keeps divers out of harms way and enables more frequent under-hull inspections.

2. Workbench Strengths

The workbench can adequately handle this mission. The workbench allows the user to save where all the piers are for any port as an avoidance area. If the user knows where the ships that need to be search are moored, the user can quickly convert previous missions to fit the needs of the current mission.

3. Workbench Weaknesses

One weakness in this mission area is lack of control of the sensors area. To make this mission area more effective, the workbench needs a customized agenda mission-planner capability. To make this work the user needs to tell the workbench where the ships are, where the piers and other obstacles, and what type of search patterns are best utilized. The workbench can then create this mission for the user, which the user can modify it to make it more efficient. This tool pattern of creating tactical decision aid (TDA) customized to specific robot missions is a promising concept that should be evaluated for other mission areas as well.

4. Example Mission

For this mission an UUV searches two ships. The first ship performs a quick sweep of the hull. The UUV on the second ship performs a complete hull survey. The UUV does this mission while avoiding the piers in the harbor.

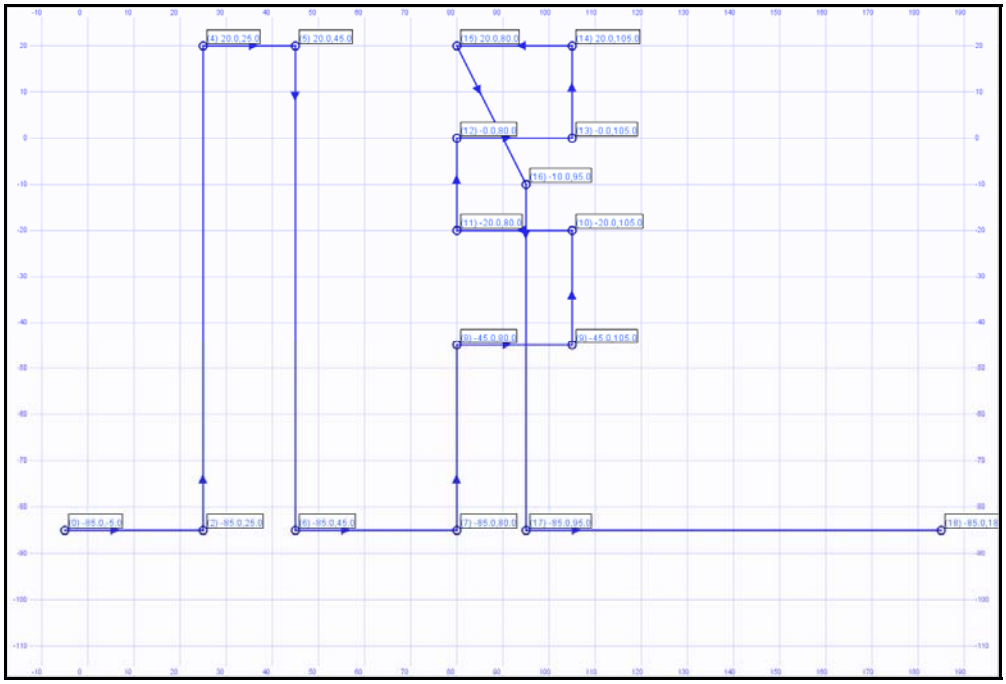

Figure 41. The Inspection and Identification mission as planned in the AUVW

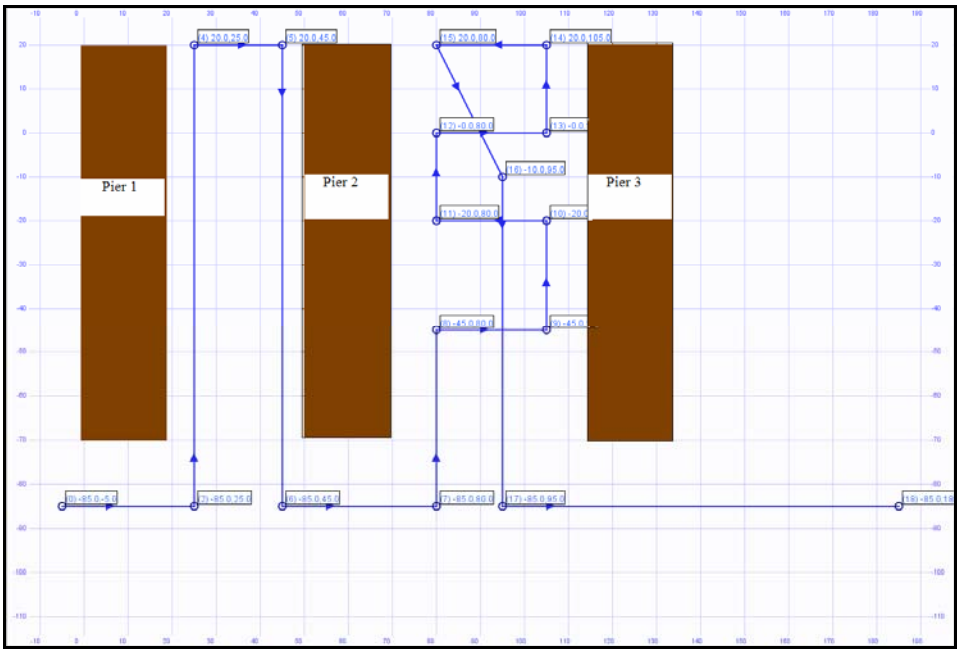

Figure 42. The Inspection and Identification mission with piers over the mission plan.

0. **UUV Position** *The launch point*
1. Make Speed
2. **UUV Waypoint**
3. Meta Command
4. **UUV Waypoint** *The start of the ID survey of a ship*
5. **UUV Waypoint**
6. **UUV Waypoint** *The end of the ID survey of a ship*
7. **UUV Waypoint** *Start of the hull survey of the second ship*
8. **UUV Waypoint**
9. **UUV Waypoint**
10. **UUV Waypoint**
11. **UUV Waypoint**
12. **UUV Waypoint**
13. **UUV Waypoint**
14. **UUV Waypoint**
15. **UUV Waypoint**
16. **UUV Waypoint**
17. **UUV Waypoint** *The end of the hull survey*
18. **UUV Waypoint** *The recovery point*
19. Quit

Figure 43. The AVCL commands for the Inspection and Identification mission

F. OCEANOGRAPHY

1. Summary of Mission Requirements

Collecting data about the ocean can be a dull job that manned platforms often have to complete. Robots can better perform this mission in turn allowing manned platforms to complete other missions. To accomplish this mission a robot patrols an area of the ocean to collect data like water temperature, current speed, or salinity. The oceanographic survey mission is further examined in detail in (Seguin).

2. Workbench Strengths

The Open Map feature allows the user to easily plan an oceanographic mission because the user can plan the mission over a map of the targeted area. This functionality allows the user to see where the robot will be operating rather than entering coordinates.

3. Workbench Weaknesses

The recurring theme through these missions is that AVCL and thus the AUVW cannot control a robot's sensors which are needed to complete this mission. The workbench needs to allow the user to specify an area that oceanographic data needs to be collected, the search pattern needed, and time required for the missions.

4. Mission Example

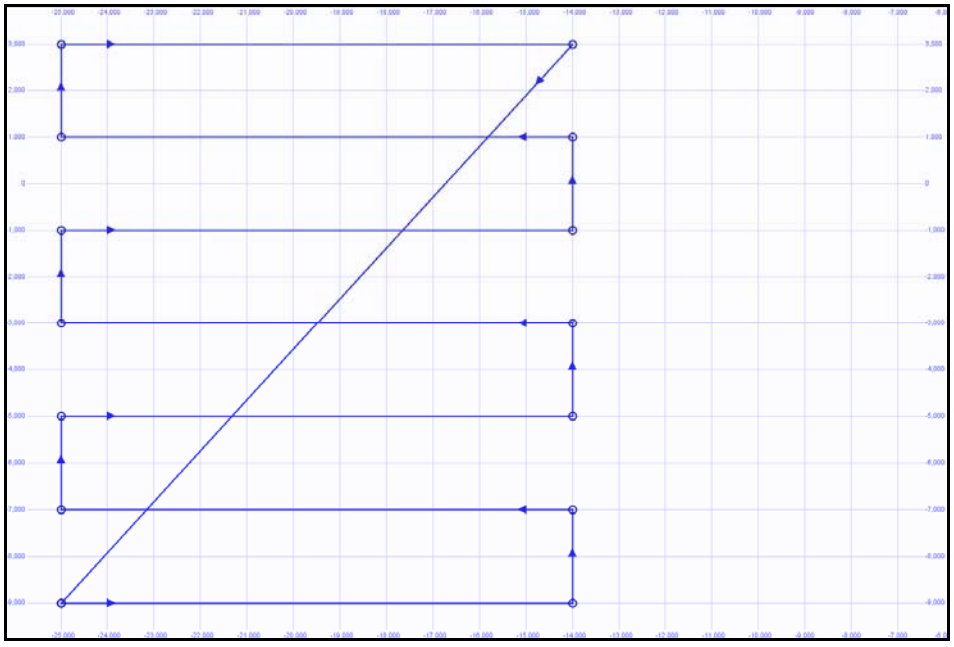

Figure 44. The Oceanography mission planned in the 2D mission planner

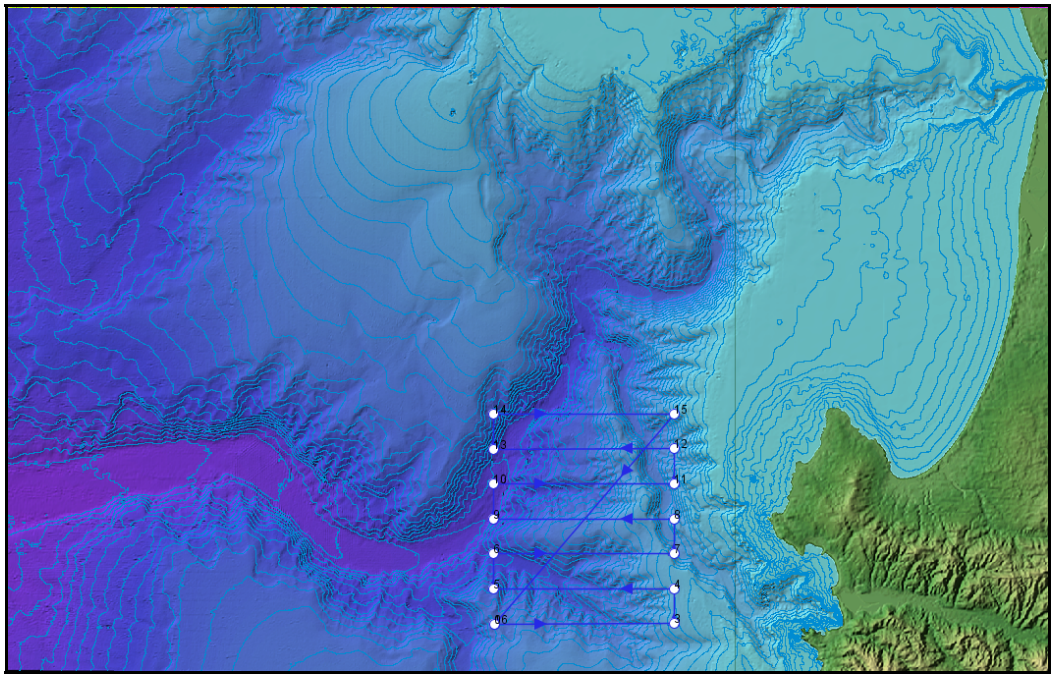

Figure 45. The oceanography mission viewed in the Open Map viewer

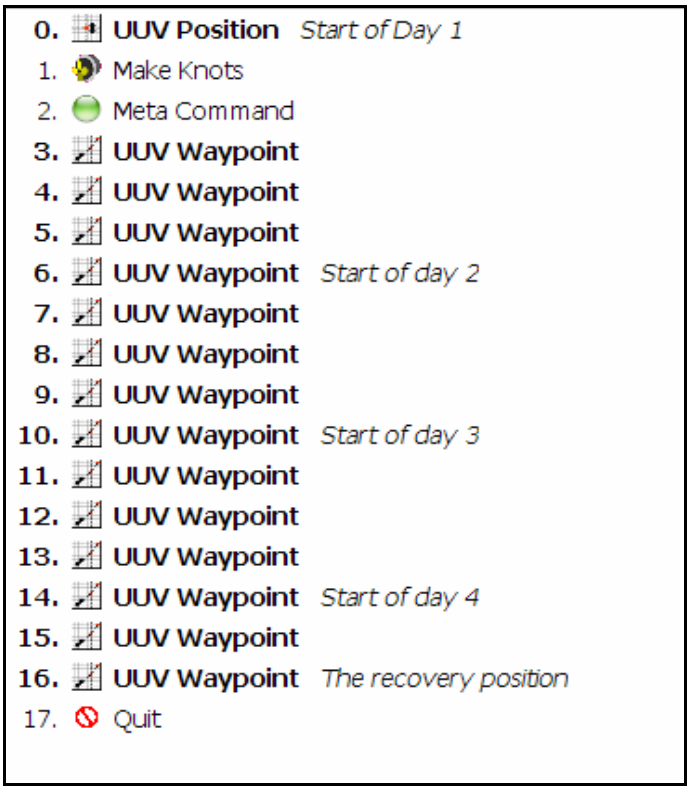
0. UUV Position Start of Day 1
1. Make Knots
2. Meta Command
3. UUV Waypoint
4. UUV Waypoint
5. UUV Waypoint
6. UUV Waypoint Start of day 2
7. UUV Waypoint
8. UUV Waypoint
9. UUV Waypoint
10. UUV Waypoint Start of day 3
11. UUV Waypoint
12. UUV Waypoint
13. UUV Waypoint
14. UUV Waypoint Start of day 4
15. UUV Waypoint
16. UUV Waypoint The recovery position
17. Quit

Figure 46. AVCL Commands for the exemplar oceanography mission

G. COMMUNICATIONS

1. Summary of Requirements

Communicating is a requirement for coordinating maneuvers for vehicles. Unmanned vehicles can either act as a network node for manned vehicles. Unmanned vehicles act as the eyes and ears for manned platforms in foreword deployed areas.

2. Workbench Weaknesses

The AUVW has minimal support of this mission area. This mission area requires that different robots have to work together and rely on one another to complete the mission. For this mission a UAV and USV patrol an area while waiting for a message. Once those vehicles receive a message, the vehicle has to respond to that message. Currently, the AUVW does not let vehicles the ability to communicate with one another. Furthermore, the workbench does not allow the robot to respond to conditions in its environment.

3. Workbench Strengths

The workbench can outline the various missions, however, it cannot show how the various missions interlink. The workbench has minimal support for this mission. Several features are needed to be added to the workbench. The user needs to see how the vehicles interlink, define what the robot will do when it receives certain mission, and also statistics if the robot is acting as a network node.

4. Mission Examples

This mission involves a UUV, UAV, USV, and a manned platform. The manned platform in this scenario launches a UUV whose task is to clear a minefield. Once the minefield is cleared, the UUV will communicate with the USV who then will communicate with the UAV. The UAV will then communicate with the mother ship and a satellite telling that the operations area is cleared.

H. PAYLOAD DELIVERY

1. Summary of Requirements

This mission is a support mission for other missions. The premise for this mission is that a UUV will move to a predetermine location to drop off supplies for unmanned vehicles future mission or for SOF operations. Unmanned vehicles can covertly deliver supplies without the enemy knowing about it.

2. Weaknesses

The weakness of this mission area is that a metaCommand is necessary to command the robot to release its cargo. An AVCL script command is needed to perform this mission. NPS will also need a vehicle that can perform this mission so it can be tested.

3. Strengths

The workbench can easily order a vehicle to a desire location which is critical to the success of the mission. The Open Map allows the user to use different missions to plan the mission. Terrain features are necessary to plan a payload mission accurately.

4. Mission Example

The UUV in this mission moves from the mother ship to predetermined locations to deliver supplies for future operations. After the vehicle delivers the supplies, it moves back to the ship.

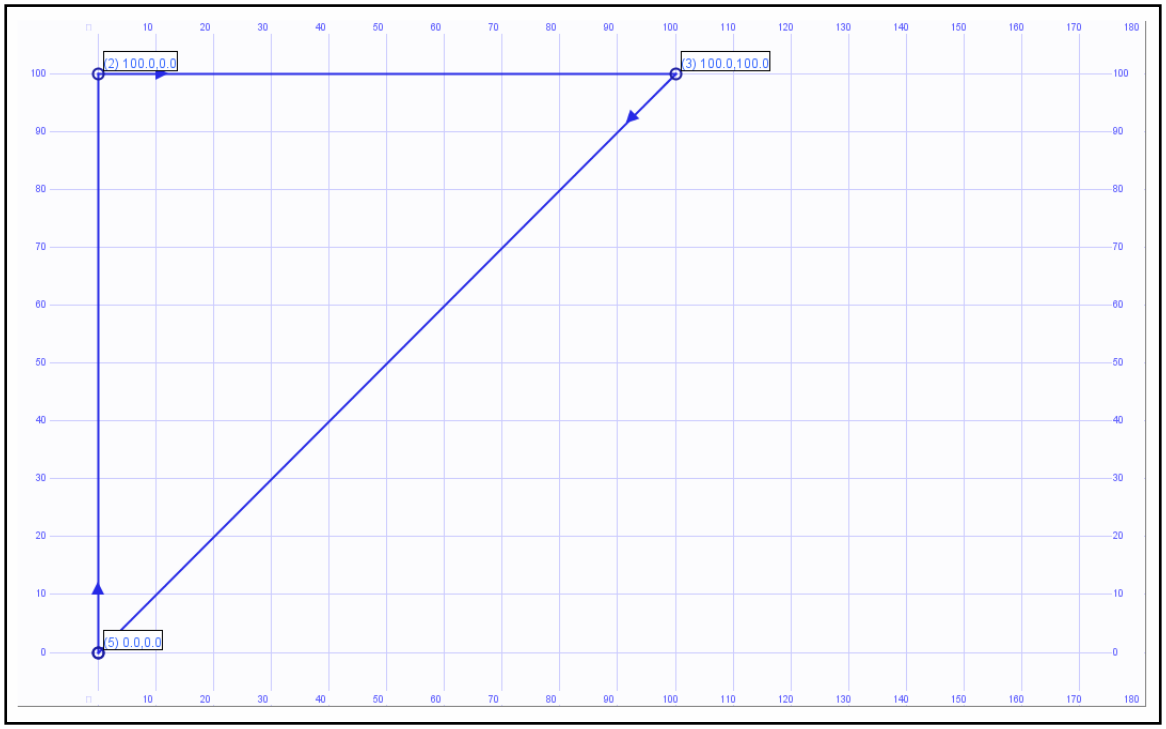

Figure 47. Payload mission shows the vehicle moving to predetermined locations to deliver the payload, and then returns to the recovery position.

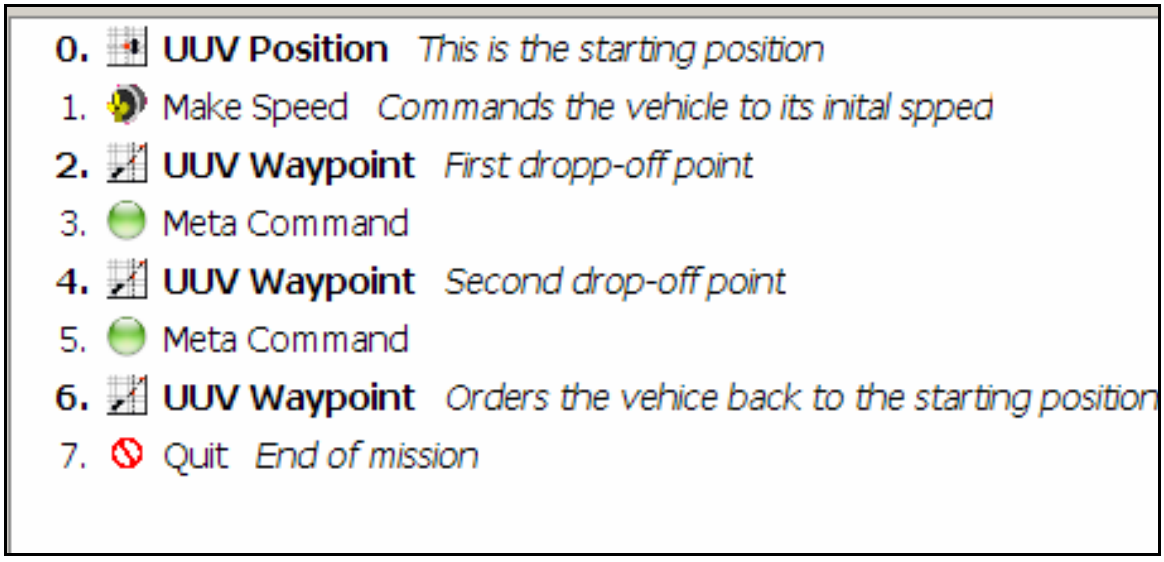
0. UUV Position This is the starting position
1. Make Speed Commands the vehicle to its inital spped
2. UUV Waypoint First dropp-off point
3. Meta Command
4. UUV Waypoint Second drop-off point
5. Meta Command
6. UUV Waypoint Orders the vehice back to the starting position
7. Quit End of mission

Figure 48. The AVCL commands for the payload mission

I. INFORMATION OPERATIONS (IO), ELECTRONIC ATTACK (EA), AND SUPPRESSION OF ENEMY AIR DEFENSE (SEAD)

1. Summary of Mission Requirements

The common thread between information operations (IO), electronic attack (EA), and suppression of enemy air-defense (SEAD) is jamming. Jamming is an AVCL agenda mission capability, which the user can order a robot to jam a certain region.

2. Workbench Strengths

This mission area has the potential to be successful because of the ease to jam certain areas with energy. To make this a better mission area a subject matter expert needs to help develop the mission area functionality.

3. Workbench Weaknesses

This is the weakest mission area in the AUVW. The AUVW has an agenda mission for jamming, but this mission does not run. Support for this mission area needs to be fixed and then tested with actual robots to ensure that it works properly.

4. Mission Example

The following simple mission shows an AUV flying to a location and jamming a bandwidth of frequencies.

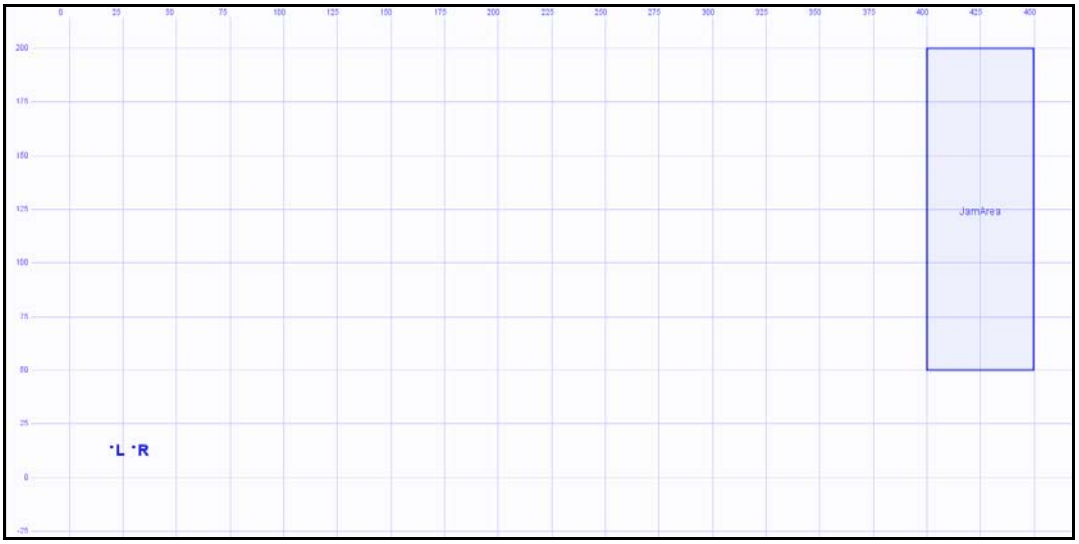

Figure 49. Jam mission planned in the 2D planner

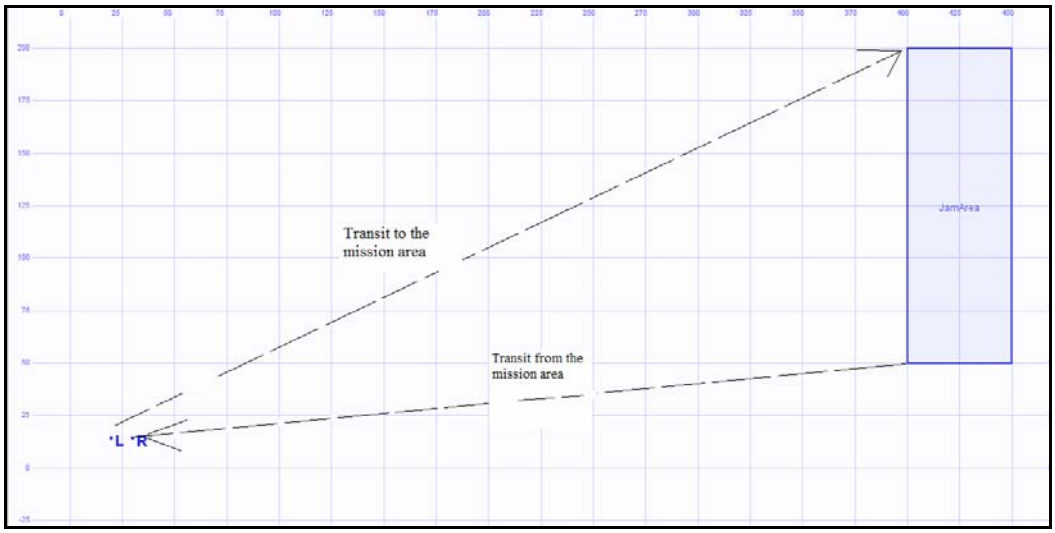

Figure 50. Jam mission in the 2D planner with user annotations

J. STRIKE

1. Summary of Requirements

Strike is the least critical mission area that unmanned vehicles currently have to complete. Teleoperatored UAVs currently are the only vehicle performing strike missions.

2. Workbench Strengths

The AUVW currently cannot perform this mission. The workbench can only order vehicles to move to a location and then use metaCommands to complete the mission.

3. Workbench Weaknesses

The AUVW does not have the necessary tools to perform this mission area. When a vehicle is launching weapons that will kill people, the software needs to ensure that it can perform that mission 100% of the time. This mission is the least critical mission area, which will allow the workbench to acquire the needed functionality.

4. Mission Example

In this scenario, an UAV flies to a target to send the coordinates back to an USV who then launches a strike against the target.

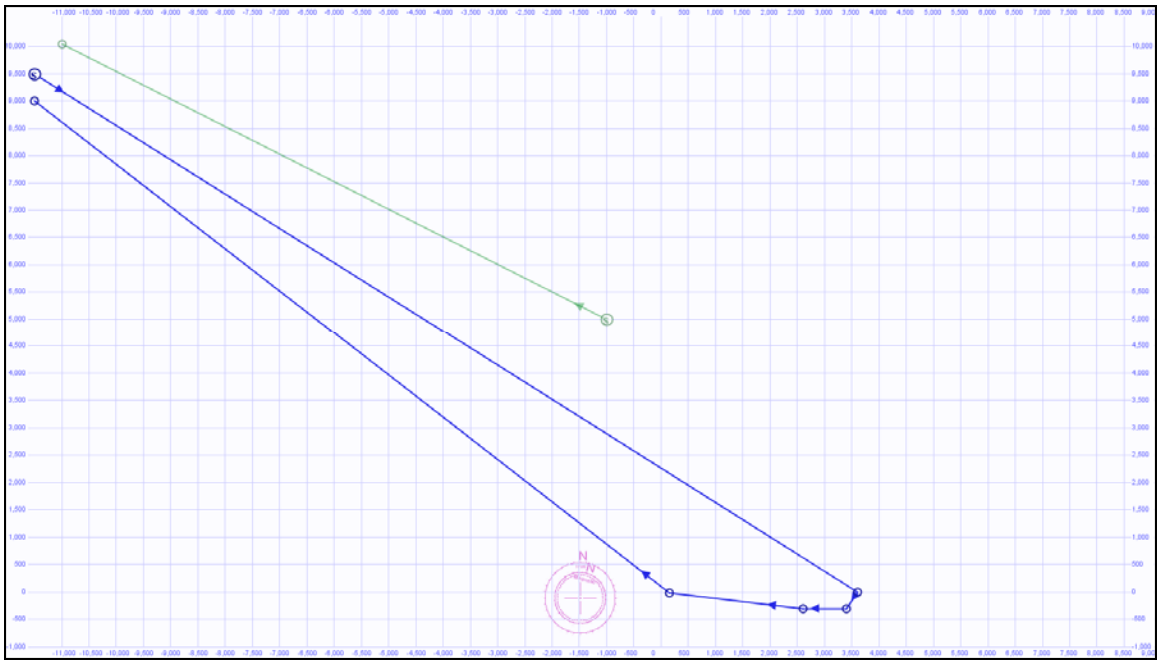

Figure 51. The strike mission planned in the 2D mission planner

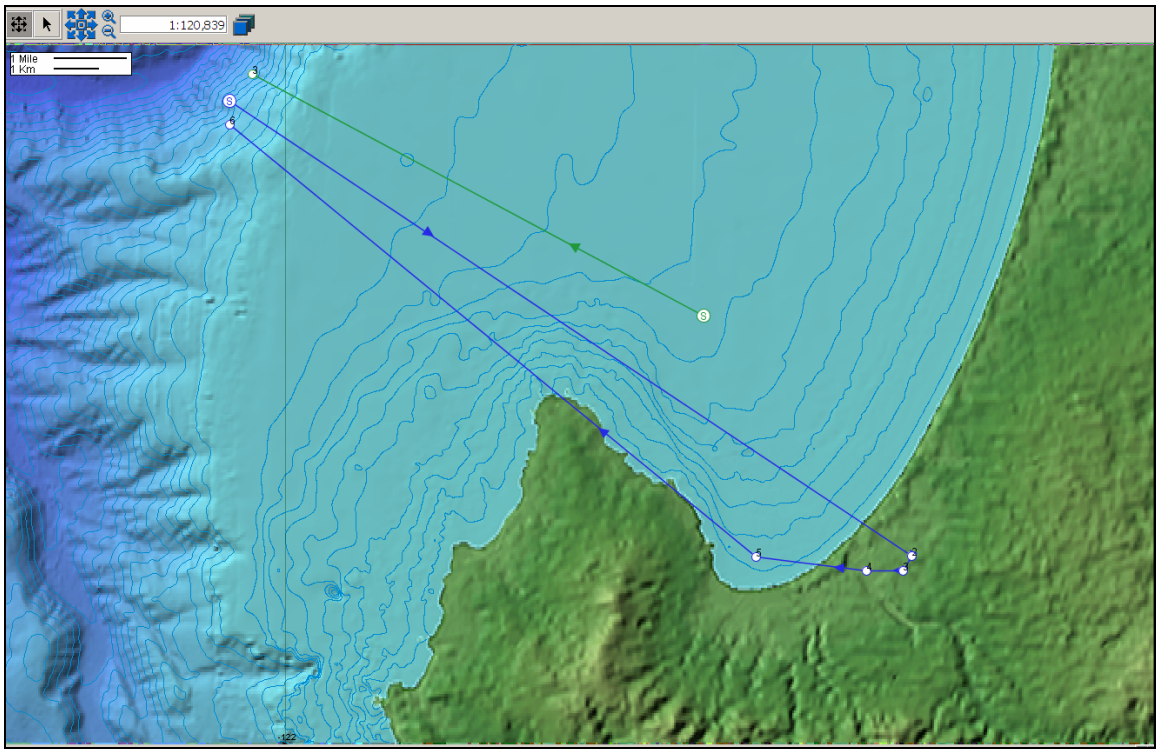

Figure 52. The strike mission in the Open Map viewer

0. **UAV Position**
1. Make Speed
2. **UAV Waypoint** *Target location*
3. **UAV Loiter** *Wait for strike*
4. **UAV Waypoint** *Move back to recovery*
5. **UAV Waypoint**
6. **UAV Waypoint** *Recovery point*
7. Quit

Figure 53. UAV AVCL commands for the strike mission

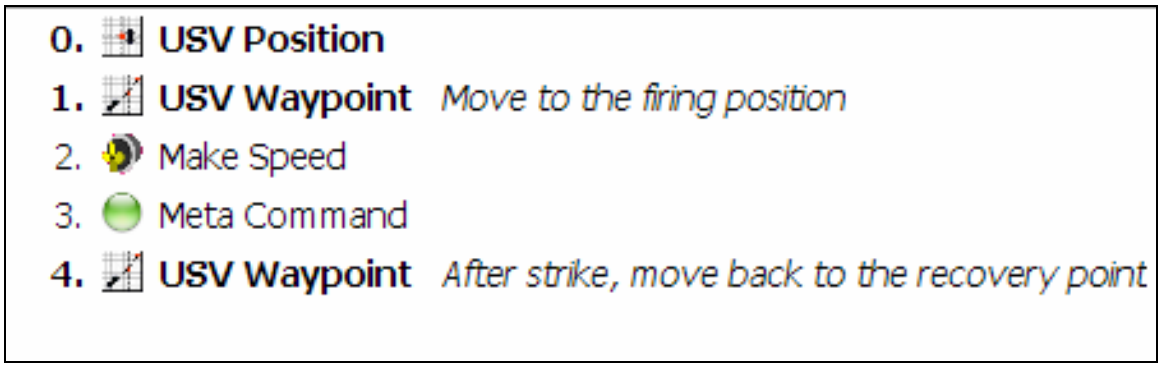
0. USV Position
1. USV Waypoint Move to the firing position
2. Make Speed
3. Meta Command
4. USV Waypoint After strike, move back to the recovery point

Figure 54. USV AVCL commands for the strike mission

K. AUVW GRADE OF MISSION AREAS

The AUVW cannot fully perform any of the mission areas outlined by the various master plans, however, it close to completing a majority of the mission areas. This is not surprising because the workbench has just recently reached the maturity to be a tactically feasible mission planner. Nevertheless, a programmer working with a subject matter expert for each of the mission areas can easily fix any deficiencies in that particular area. As the workbench matures and its users gain experience preparing each type of mission area, some desired features will remain unknown. Experimentation and evaluation is critical in the development of the workbench

Table 10 gives the workbench a grade based off of the AUVW current capabilities. The grading scale that was used was complete, partial, or future work. Complete means that the AUVW totally supports the mission type and no more work is needed in this area. Partial means that the AUVW can support some functionality in the mission area but still needs to be improved. Future work means that the AUVW supports this mission area and needs considerable work to complete the mission area.

Mission	Grade
ISR	Partial
Mine Warfare	Partial
Inspection/ID	Partial
Oceanography	Partial
Communications	Future work
Payload Delivery	Partial
IO, EA, SEAD	Future work
Strike	Future work

Table 10. Grades for AUVW mission areas

L. SUMMARY

This chapter merged the different master plan's mission areas into common missions. The mission areas that unmanned vehicles are expected to perform are ISR, mine warfare, inspection and ID, oceanography, communications, payload delivery, IO EA SEAD, and strike. The most important mission for unmanned vehicles is ISR. This chapter explains an exemplar mission that was planned in the workbench, the strengths and weaknesses of planning the mission in the workbench, and screen shots of the missions.

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VII. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

Unmanned vehicles are and will continue to be an important asset to the U.S. military. Future combat platforms of the Navy will rely on unmanned vehicles to aid them in completing their missions. The Navy has more mission areas in variety of locations across the globe since the end of the Cold War. The Navy has to complete more mission areas but with less people in the Navy. Unmanned vehicles are a cheaper alternative than buying conventional platforms because unmanned vehicles are force multipliers. Therefore, a consistent interface for rehearsal, replay, and real-time control of different UAV, USV, UUV platforms is needed. The AUVW shows that such a tool is possible. Thus a coherent C4I of robots with diverge fleet assets is also feasible.

Unmanned vehicles are expected to perform the dull, dirt, and dangerous missions. The most critical mission for unmanned vehicles to perform are ISR missions. UAVs, USVs, ands UUVs have different capabilities. However, the different authoritative references vary in details on details but nevertheless are consistent in the missions of unmanned vehicles.

The AUVW has a majority of the capabilities needed for supporting operational requirements of naval unmanned systems. However, it lacks some functionality which would make it tool that the fleet could use. The AUVW has the ability to be upgraded to add functionality that the workbench lacks currently. In the last year, the AUVW has dramatically changed with the addition of Open Map, telemetry plots, the ability to replay robot's missions, and the ability to make a project for related missions. There is current work being done is to be able to change 3D terrain and loading 3D models depending on the missions. To be able to add the most important capabilities to the workbench, implementers need to know what most needs to be programmed. This thesis exposes some areas that of the workbench that need to be added or improved.

B. RECOMMENDATIONS FOR FUTURE WORK

1. Mission Areas

AVCL development needs to continue to support further mission areas. Chapter VI, outlines some of the deficiencies that need to be fixed. Once they are fixed AVCL will be able to support the mission areas outlined by the master plans.

2. Ability to Change Satellite Imagery and 3D Terrain

This feature has improved dramatically in the last year. The AUVW can access 3D scenes from Bremerton, Washington, Monterey Bay, San Clemente Island, and from Panama City, Florida. This has shown the potential of having a 3D scene for anywhere in the world. For the fleet to be able to use the AUVW, the user needs to be able to enter any latitude and longitude on the Earth, which will show the terrain, current satellite imagery, and terrain features. This feature allows the user to have greater situational awareness of the current operating area. X3D Earth is the primary strategy for further developing this capability.

3. Annotating 2D Mission Plots

The 2D mission planner does a good job in presenting the tracks for the robot missions. 2D pictures, geometric shapes, arrows, and text annotations overlaying a mission track can aid in the creation of reports for missions. Examples of pictures needed are combat platforms to show where the robot is operating in relation to its mother ship, mines, or buoys.

4. Add Viskit for Statistically Analysis of Simulated Missions

AUVW can be a better rehearsal tool for operators planning missions. Viskit can allow competing ideas on a mission plan to be solved through quantitative analysis rather than subjective opinions. This feature will be helpful for agenda missions because agenda based missions follow heuristics to plan missions. Therefore, each agenda mission run is different. The user might run the same agenda mission with hundreds of tactical or environmental variations. Then a statistical tool might predict which run was

the best based on preset criteria and measures of effectiveness. Such a capability will allow user to select the best available mission parameters (Seguin).

5. Battery Life Predicators

One of the biggest constraints on unmanned vehicles is power due to their size. Some unmanned vehicles consume fuel while others use batteries. It is important for a user to know how much fuel a mission is going to take before a mission is run, so that a UV might successfully complete its mission and return to base. A visible representation of the battery life and power consumption will provide useful insights to an operator. A simple battery-life model is already implemented further experimentation and modeling is needed to make this feature an effective capability.

6. Add SAVAGE Modeling Analysis Language (SMAL)

SMAL is metadata that is inserted into 3D models. The metadata includes data on the vehicles physical and performance parameters. Currently SMAL is used in the Savage Studio Scenario-authoring tool and works with Viskit (Rauch).

SMAL metadata might help users who have to control multiple robots of different types. The problem with creating missions for different types of robots is that different robots have different performance capabilities. It will save the user time and energy if the information of each robot was available while planning missions. This will prevent the user from giving a robot a command it cannot perform. Also, the user will not have to memorize or look up tables for each type of robot.

7. Collision Detection

The X3D visual scene allows users to see the vehicles and sensors moving around in the 3D world. However, this is not utilizing the 3D component to its potential. When the user plans a mission it is possible that the mission inadvertently commands to a robot to collide with the Earth, such as a UUV grounding on the bottom of the shallow area or a UAV impacting a mountain. It is also possible with multiple robots operating in close proximity for a collision to occur. The user needs to be alerted if a robot comes within a

certain distance from the terrain in order to prevent a mishap from occurring. Prevention of mutual interference will be another productive capability during mission rehearsal and real-time control.

8. AVCL Controller

As of right now, the workbench is only a computer interface to control a robot. It might be easier for users to control a robot in real time with an actual controller. This way when the user needs to take control of the robot the user can actually interface such as a joystick. This might support override or teleoperation control of the robot. Such a controller might have a common interface to control any robot because of AVCL.

9. Integrate Live Camera Feed and Other Sensors

To be able to adequately control a robot in the real world or to monitor a robots progress the user must be able to see what the robot sees. To help with this experience, the operator needs to be able to decipher what the robot is sensing. This can be either a video or sonar feed, if telemetry connectivity and bandwidth is sufficient. Also, knowing other information in which the robot has accessed can be important to the operator. If the user knows certain things about the robot's environment, the user can change the mission of the robot.

10. Hybrid Commands

Currently the AUVW is capable of planning missions with either through script or agenda commands. It is sometimes necessary to plan missions that require both types of commands. This feature will allow users to customize the mission to their individual needs.

11. Pass Control

The current missions that are being performed by the AUV research group at NPS is passing control between users. A sample mission currently being performed has a ground station control a UAV, then the UAV controls a USV and upon completion of the joint mission, control reverts to the original stations. This type of coordinated-operations mission makes unmanned vehicles more useful to the war fighter.

Another example is, sometimes the person who needs to use the robot does not control or carry a robot. For instance, troops on the ground cannot carry heavy robots around. Rather the control of the robot has to be passed from the initial controller to the troops on the ground. The AUVW needs to incorporate this ability so that people know who has control of the robot. Also, the workbench standardize hand off procedure. Conceivably the AUV Workbench can serve as the actual portable ground control stations.

12. Localization

Even with the must up to date terrain and satellite data it will be outdated when the robot operators in that area. For instance, if an UAV is trying to assess the battle damage of a bombing raid over a city, the city be different due to destruction of the bombing raid. Allowing the operator to be able to see up to date imagery of its operating area, the operator can direct the robot to points of interest.

13. AVCL Commands

AVCL is a powerful asset to the workbench but it has not been fully tested yet. In the future, all the commands of the AVCL need to be tested in the real world to a command given in the workbench. With the workbench being worked on by several contributors, things that worked in the past might not work over time. Since the source code is being worked on daily, there is a chance that something that was working in the past may not work correctly with the new changes. It is important that commands are reliable and that commands given in software will mirror real world commands. Adding a unit testing capability will ensure that all capabilities remain.

When directing a robot, it is helpful to have a command given only when a pre-condition is met. This is like an *if* or a *while* condition in computer programming. While this condition is true, do command A but if this condition turns false do command B. An example of this is a vehicle conducting obstacle avoidance because a vehicle will stay at its current depth until it senses an obstacle. Once the vehicle senses an obstacle it will know to change its depth. Use of distinct AVCL agenda commands with different success and failure outcomes provides this capability.

The agenda missions in the workbench need a wizard that makes it easier to generate sophisticated missions. Agenda missions as of right now are somewhat obscure in displaying expected mission logic. The user needs to be able to specify which type of mission they want the robot to complete and then have a simple GUI to use. For this to be possible someone with operational experience with robots performing multiple missions needs to know what a robot needs to know to perform each mission. Then the subject matter expert needs to perform a quality control check to see if the robot performs how it is suppose to when performing a mission.

A future work recommendation is to test all the AVCL commands in multiple types of robots, ensuring that both the simulation and the real world command implementations match. A systematic study of the commands can find any logic errors in the simulation code. This capability can be further strengthened by integrating actual version-controlled robot software in the virtual controllers.

14. Human Systems Integration (HSI)

The AUVW has come a long ways since 1994. It might be possible for the software to be deployable in the fleet. However, for that to be an effective reality the software needs to be tested for its usability on the human side. Operators need to be able to evaluate the software and to find things that can make the software easier to understand.

A future work recommendation is to test how easy the AUVW is to understand for future operators. Tasks need to be given to the operators that would test the usability of the workbench. The time to complete the mission and user feedback will help move this study along. Ongoing work using the workbench in graduate studies has commenced this ongoing process.

15. Robots for Science Missions and Educational Support

The scope of this thesis covered robot applications for the military. Unmanned vehicles are also used for scientific research. The AUVW is also used to plan and perform scientific missions. A similar study is appropriate regarding science missions and educational support

16. Multiple Robot Cooperative Control and Communications

Individual robots can perform numerous missions independently; however, complex missions require multiple robots operating together. As vehicles operate together, communications between vehicles become vital. Currently in the AUVW, robot's missions are planned independently of each other. However, vehicles are dependent on each other for some types of missions. When an UUV searches an area for mines and does not find any mines the UUV can send a message to other robots telling them that the area does not have any mines. Once the other robots know the operating area is clear they can begin their missions. Further work is needed to extend AVCL for multiple-robot control, and provide corresponding support in The AUV Workbench to monitor and evaluate inter-robot communications.

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